

# Professor Charles A. Whitten

Levoca, Slovakia, 2007



- One of the founders for STAR Experiment
- A genuine experimentalist
- A true gentleman

(selected)

# Recent Results from STAR

**Nu Xu**

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*(<sup>2</sup>) College of Physical Science & Technology, Central China Normal University, China*





# Outline



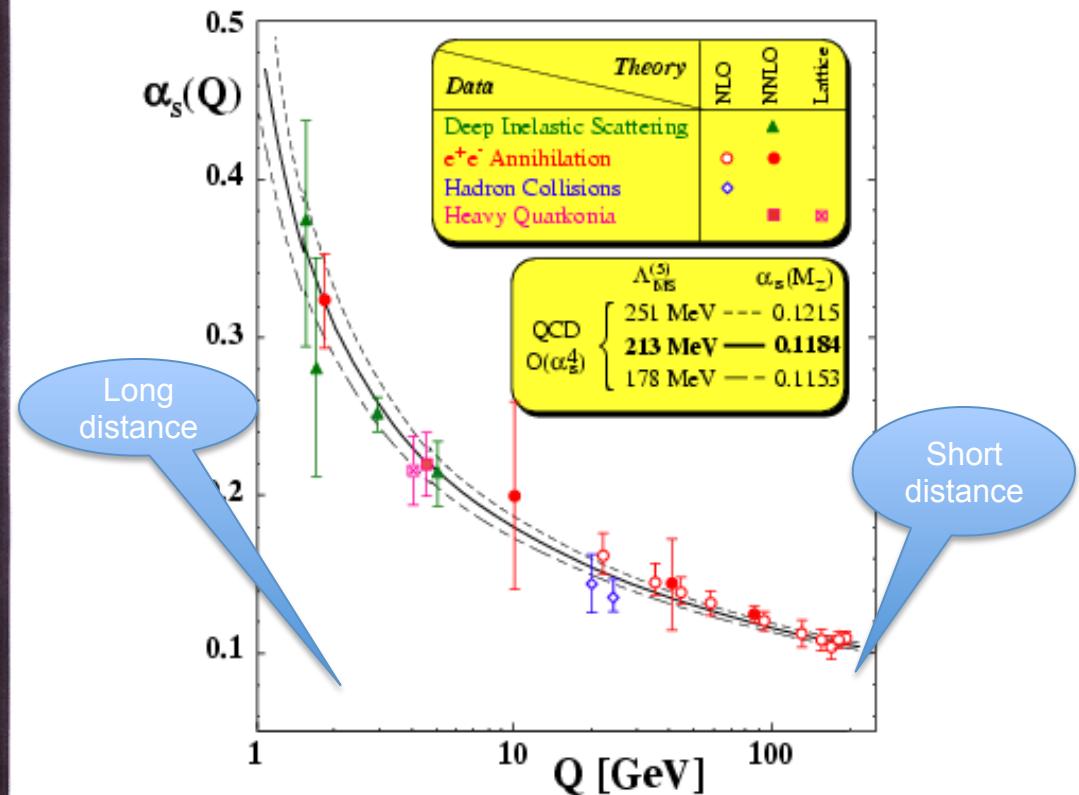
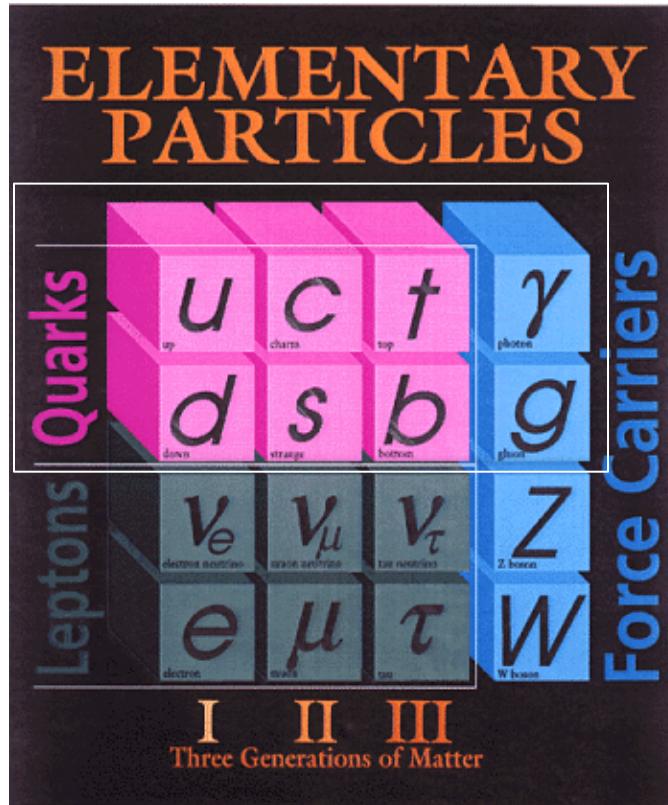
## (1) Introduction

## (2) Recent Results from RHIC

- Spin Physics
- $\sqrt{s_{NN}} = 200 \text{ GeV}$  Au+Au Collisions
- RHIC Beam Energy Scan

## (3) Summary and Outlook

# Quantum ChromoDynamics



- 1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
- 2) Little is known regarding the dynamical structures of matter with  $q, g$ .  
*E.g. the confinement, nucleon spin, the QCD phase structure...*  
Large  $\alpha_s$ , strong coupling – QCD at long distance.



**STAR Collaboration**

# **STAR Collaboration**

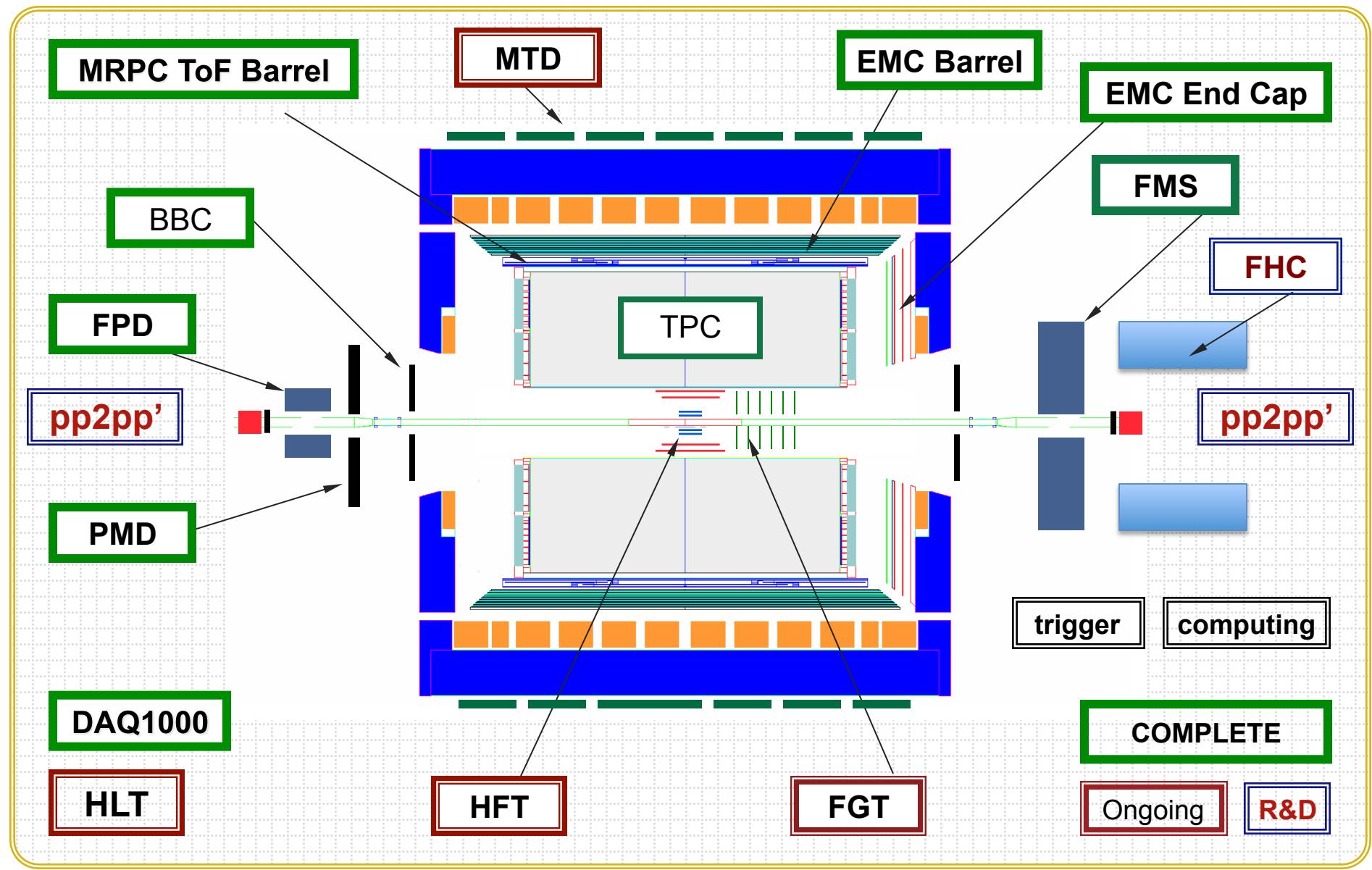
550 Collaborators

55 Institutes

12 Countries



# STAR Experiment



**MRPC Time Of Flight**

**EMC+EEMC+FMS**  
 $(-1 \leq \eta \leq 4)$

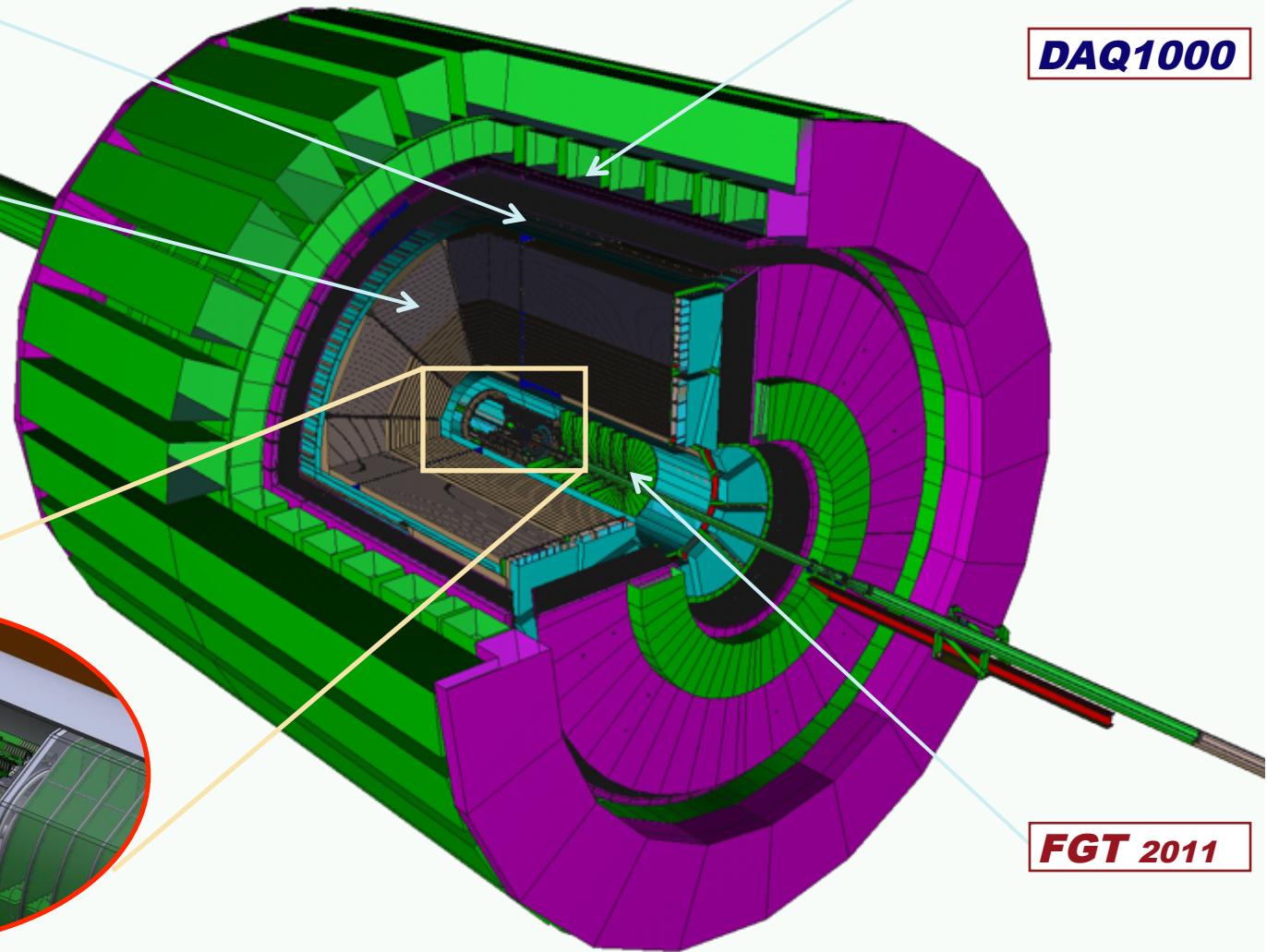
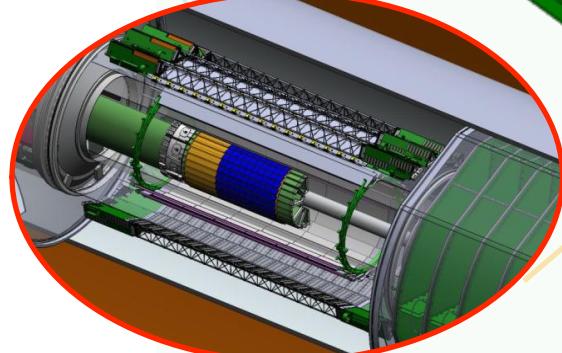
**MTD 2013**

**Time Projection Chamber (TPC)**

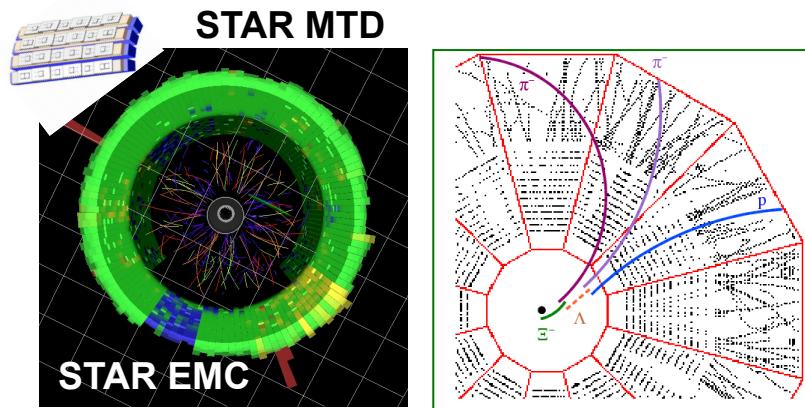
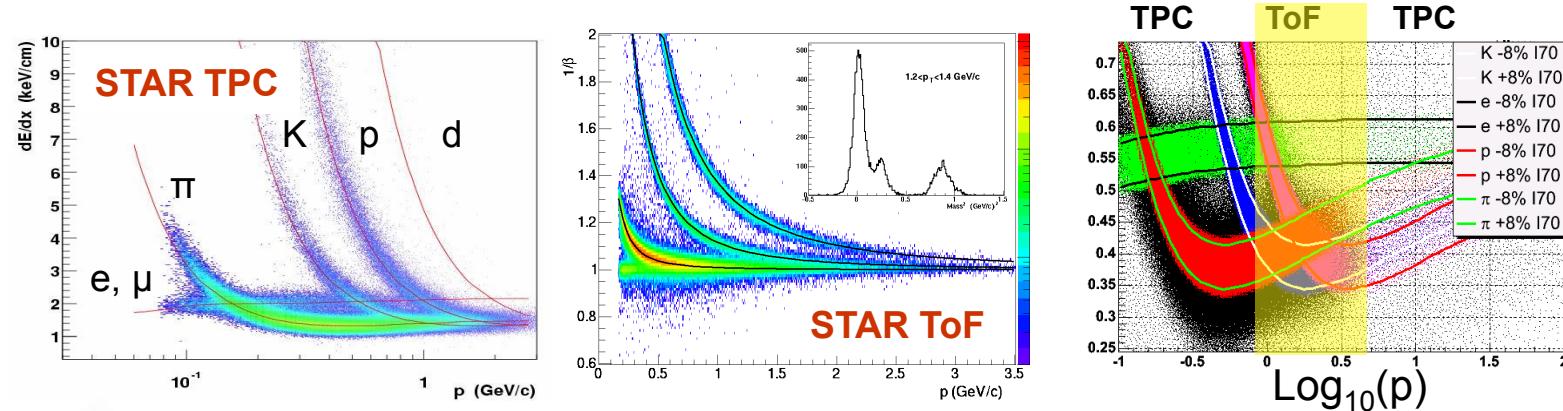
**DAQ1000**

**Heavy Flavor Tracker (HFT)  
2013**

**FGT 2011**

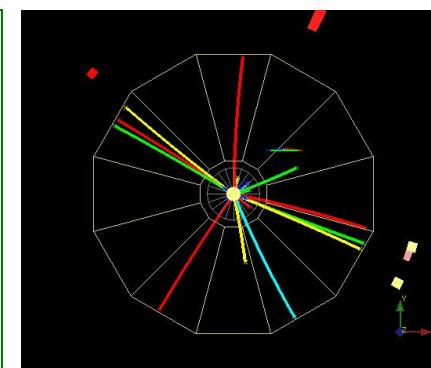


# Particle Identification at STAR

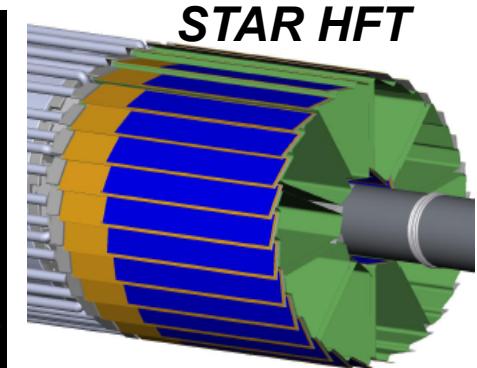


**Neutral particles**

**Strange hyperons**



**Jets**



**Heavy Quark Hadrons**

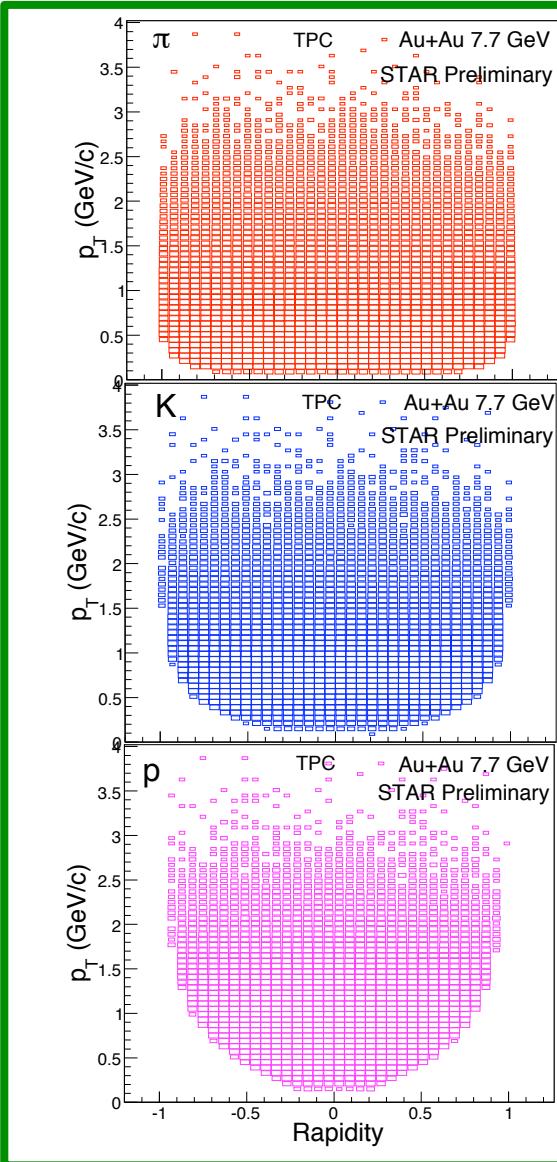
***Multiple-fold correlations for both HI and Spin physics!***



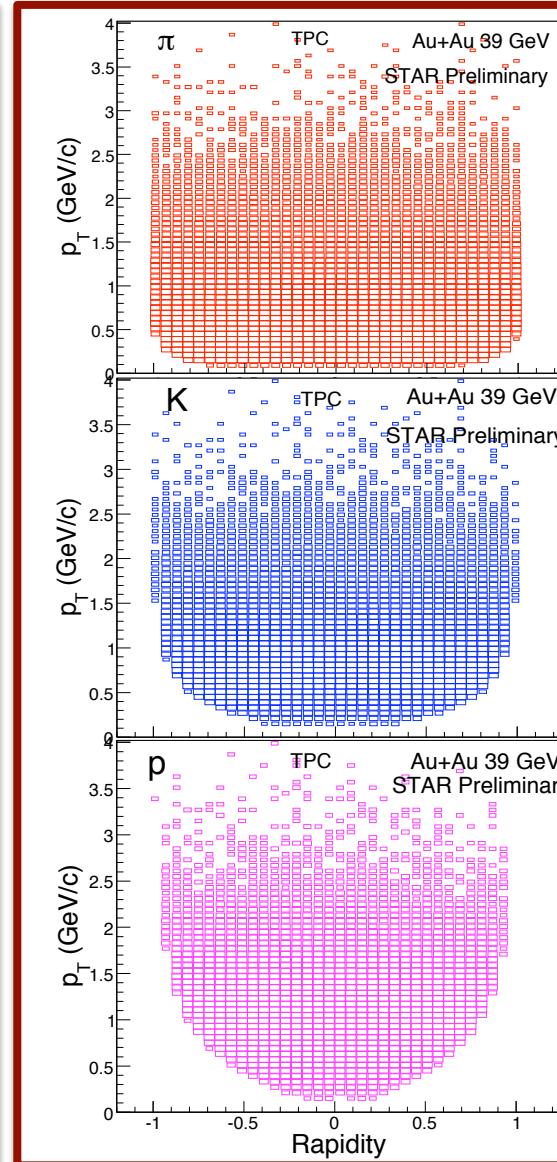
# STAR PID: ( $\pi$ , $K$ , $p$ )



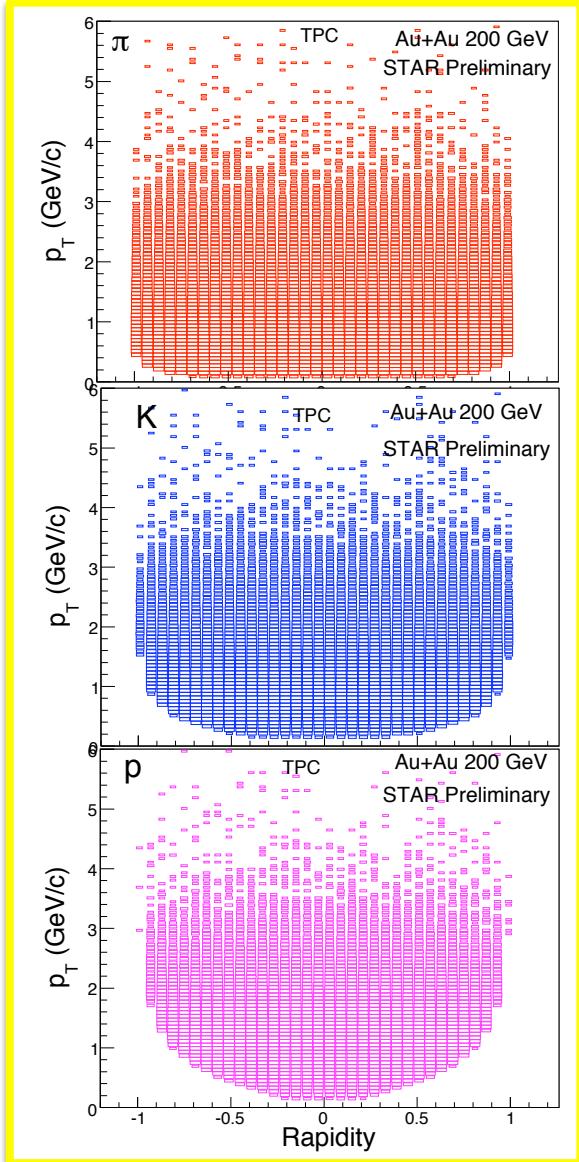
Au+Au at 7.7 GeV



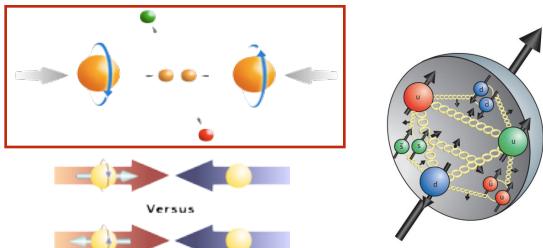
Au+Au at 39 GeV



Au+Au at 200 GeV

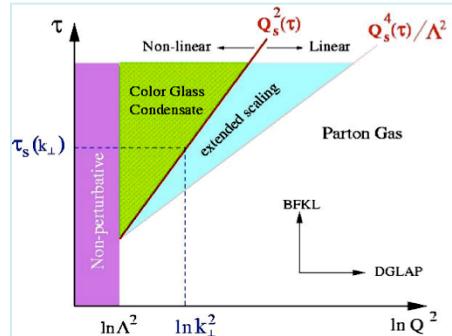


# RHIC Physics Focus



**Polarized  $p+p$  program**

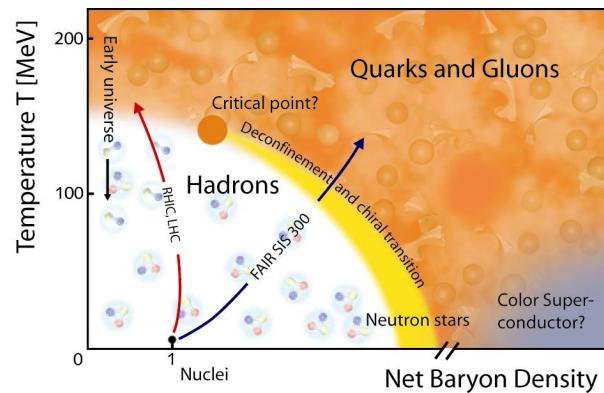
- Study *proton intrinsic properties*



## Forward program

- Study low-x properties, initial condition, search for **CGC**
- Study elastic and inelastic processes in pp2pp

2020 -  
**eRHIC**  
(eSTAR)



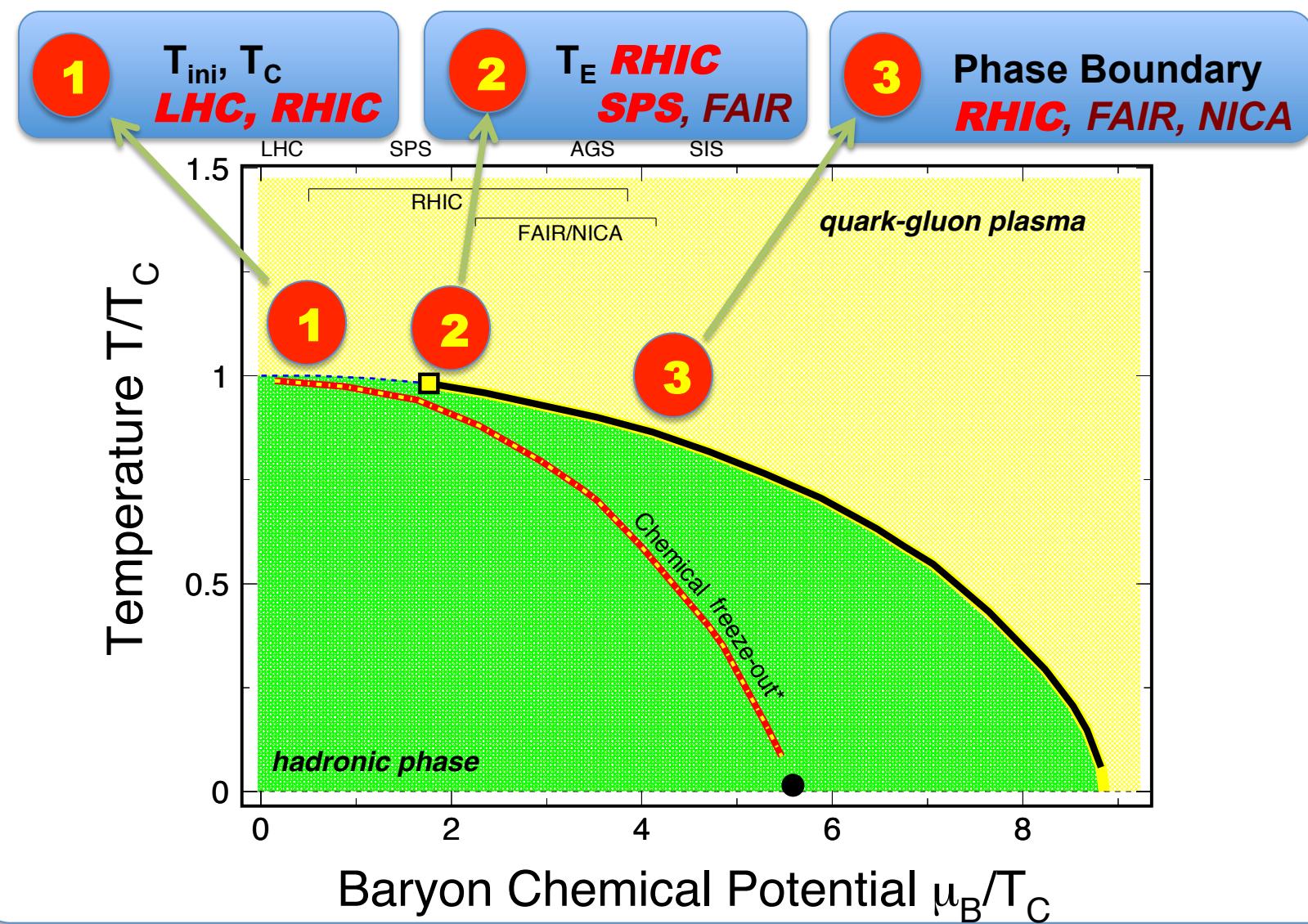
## 1) At 200 GeV at RHIC

- Study *medium properties, EoS*
- pQCD in hot and dense medium

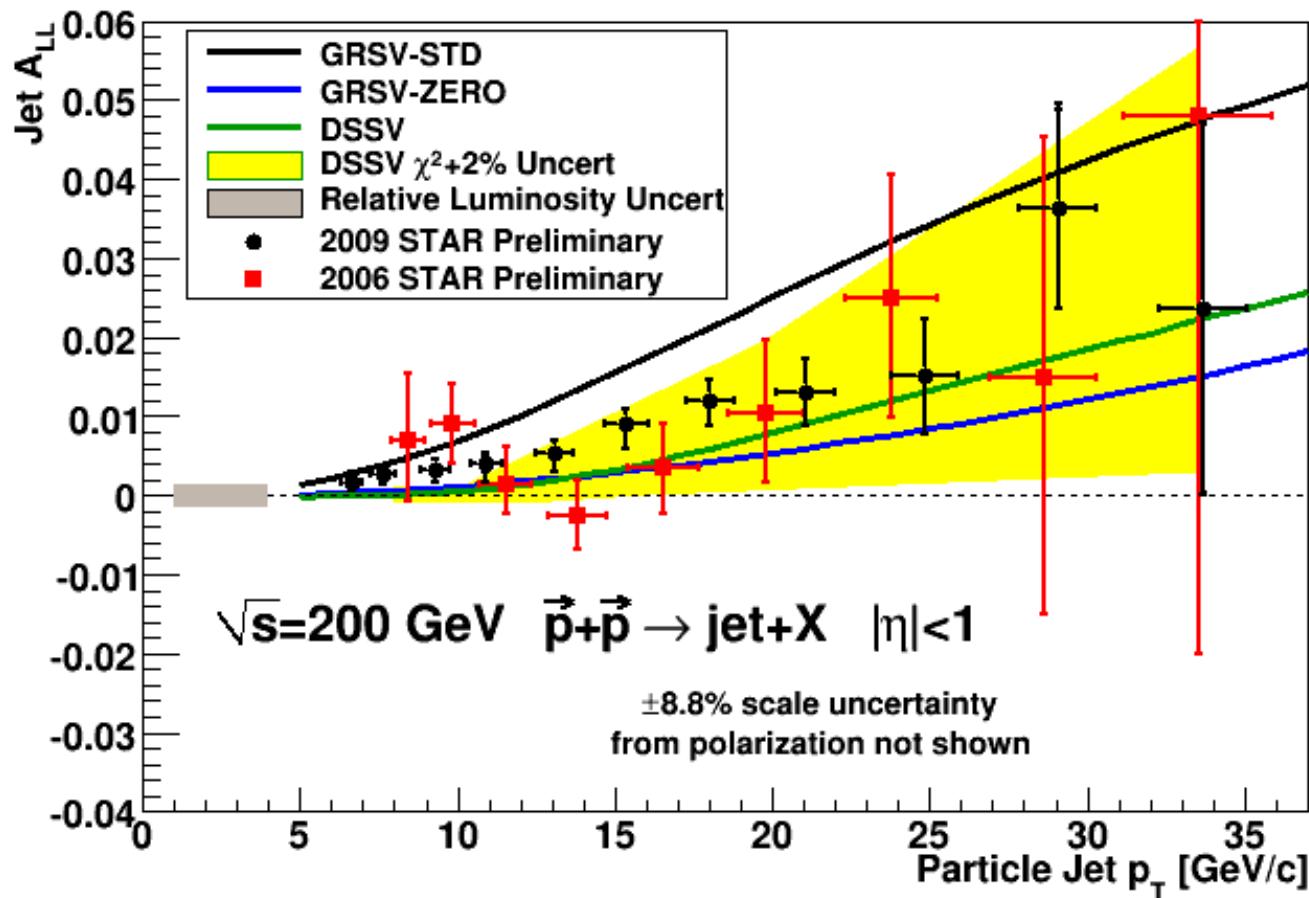
## 2) RHIC beam energy scan (BES)

- Search for the *QCD critical point*
- Chiral symmetry restoration

# The QCD Phase Diagram and High-Energy Nuclear Collisions

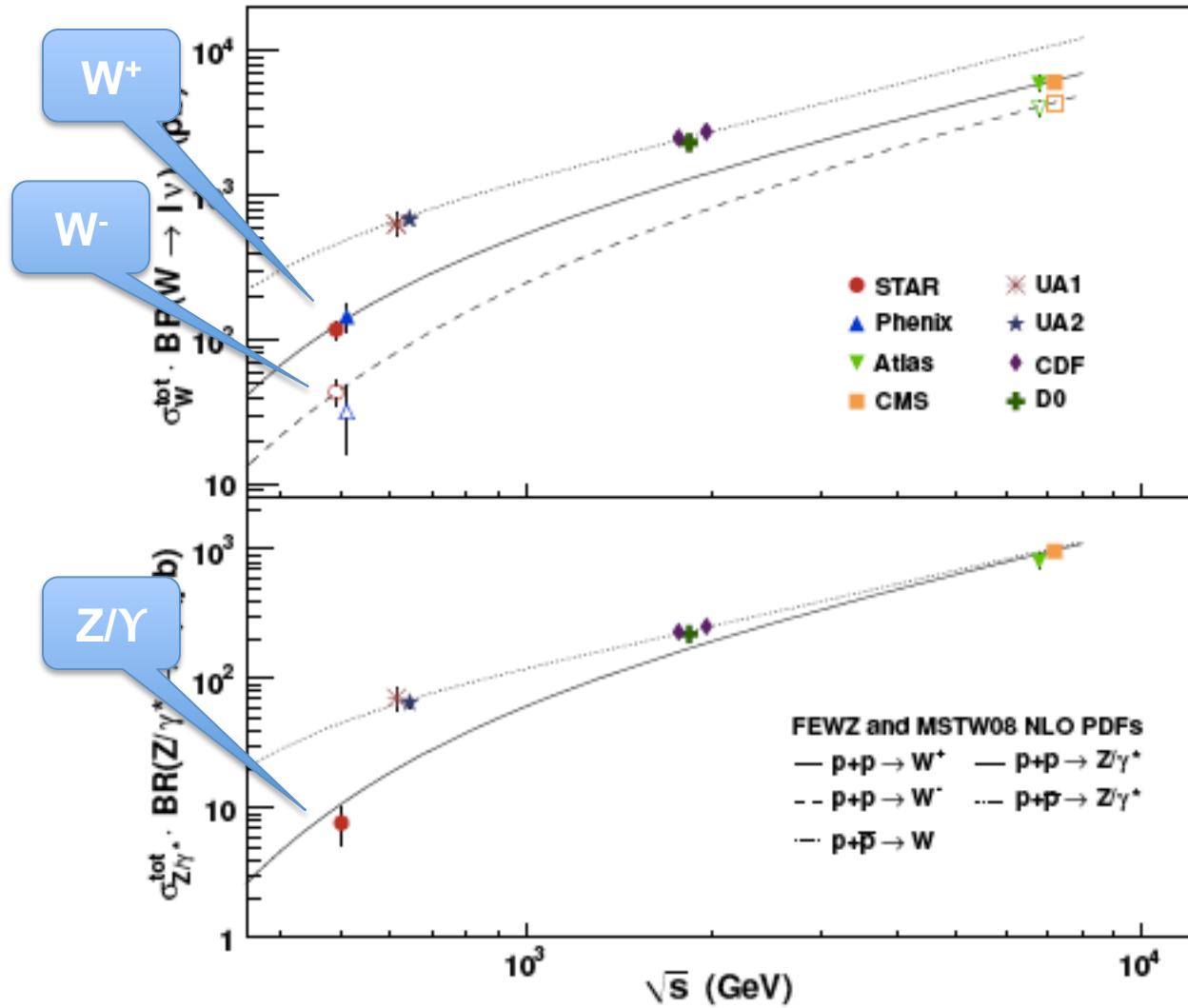


# STAR $A_{LL}$ from 2006 to 2009



2009 STAR  $A_{LL}$  measurements:

**Results fall between predictions from DSSV and GRSV-STD**

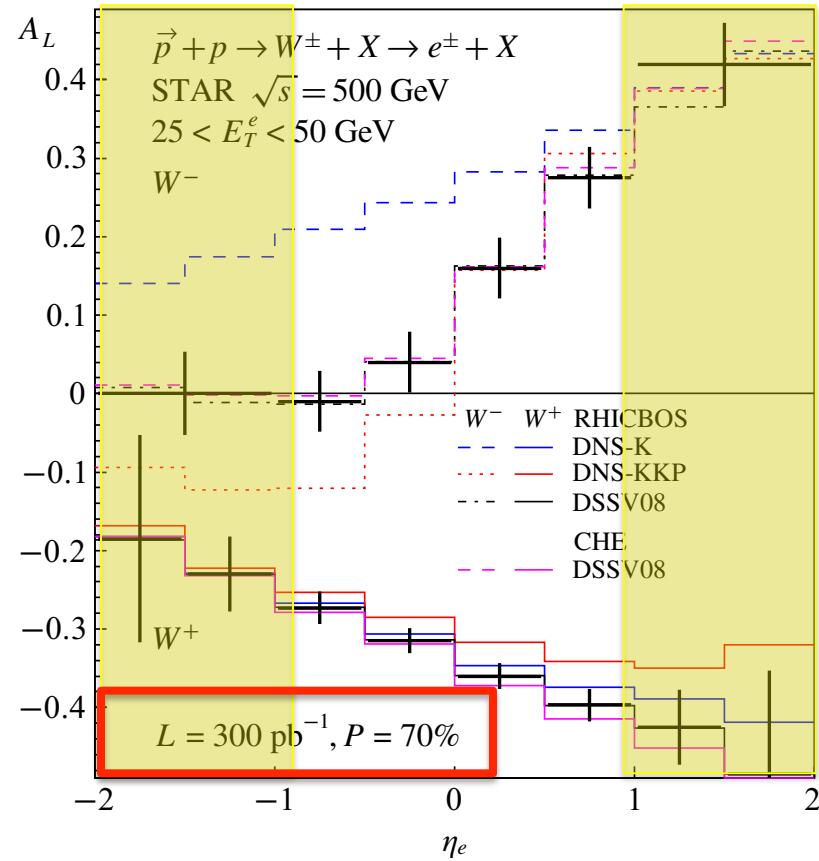
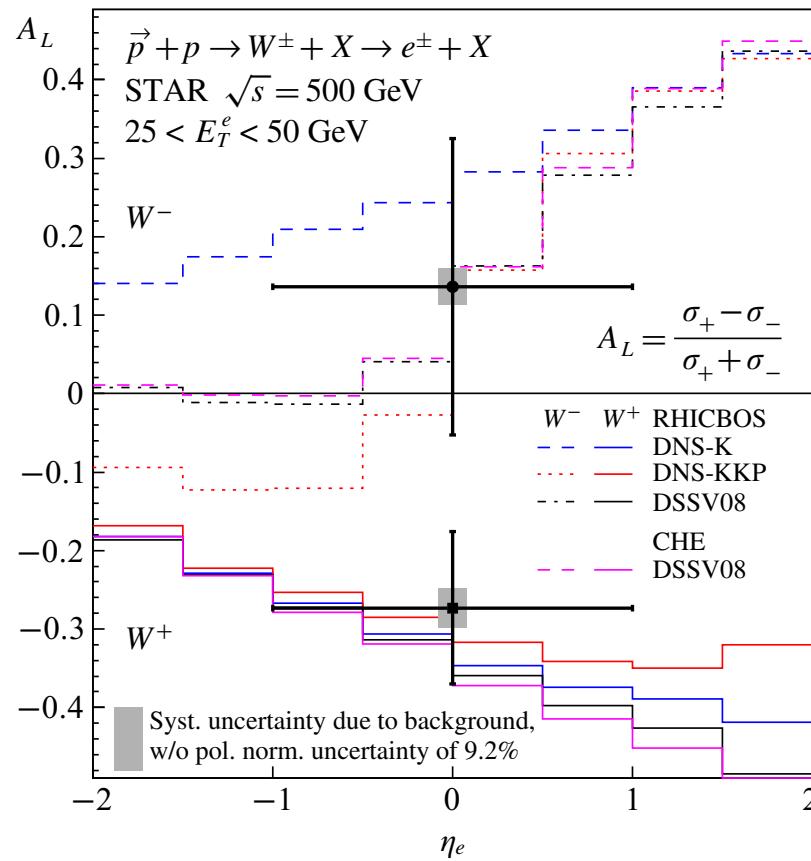


p+p collisions at  
 $\sqrt{s} = 500$  GeV

- 1) Results from NLO QCD models are consistent with STAR new data
- 2) Future high statistics W data important for flavor asymmetry of the sea quark study

\* Submitted to PRD soon

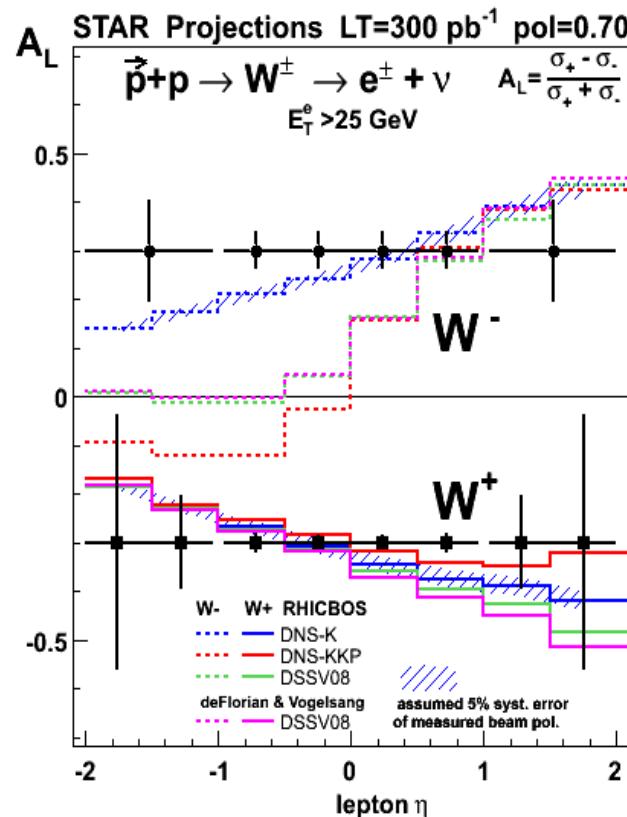
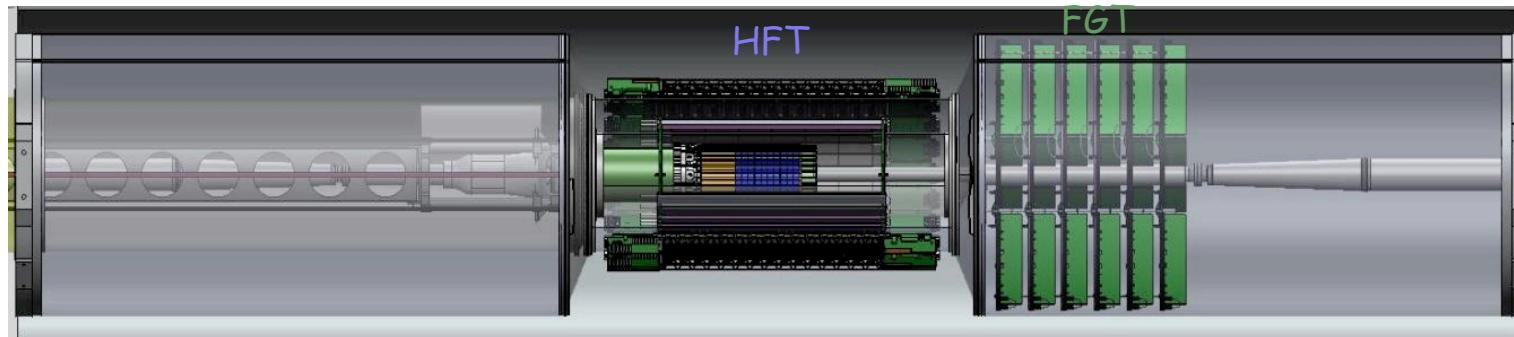
# Quark Flavor Measurements: $W^\pm$



- 1) Results\* are consistent with model: **Universality of the helicity distr. Funct.!**
- 2) Combined results of Run 9 and Run 11 reduces the error  $\sim 0.63$ .
- 3) Precision measurements require **large luminosity, high polarization** at RHIC!

\* STAR: Phys. Rev. Lett. **106**, 062002(2011).

# Forward GEM Tracker

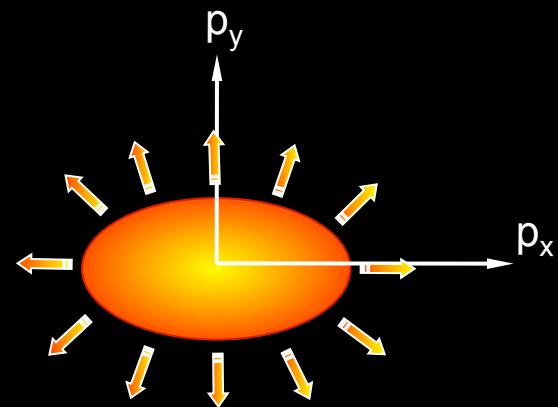
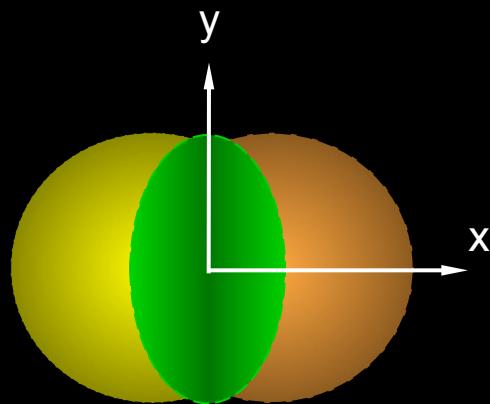


- 1) FGT: RHIC CE project
  - 2) Six light-weight triple-GEM disks
  - 3) New mechanical support structure
  - 4) Planned installation: Summer 2011
  
  - 1) Full charge-sign discrimination at high- $p_T$
  - 2) Design polarization performance of **70% or better** to collect at least 300pb<sup>-1</sup>
  - 3) **Ready\* for Run 12!**
- \* minimal configuration

# Anisotropy Parameter $v_2$

coordinate-space-anisotropy

↔ momentum-space-anisotropy

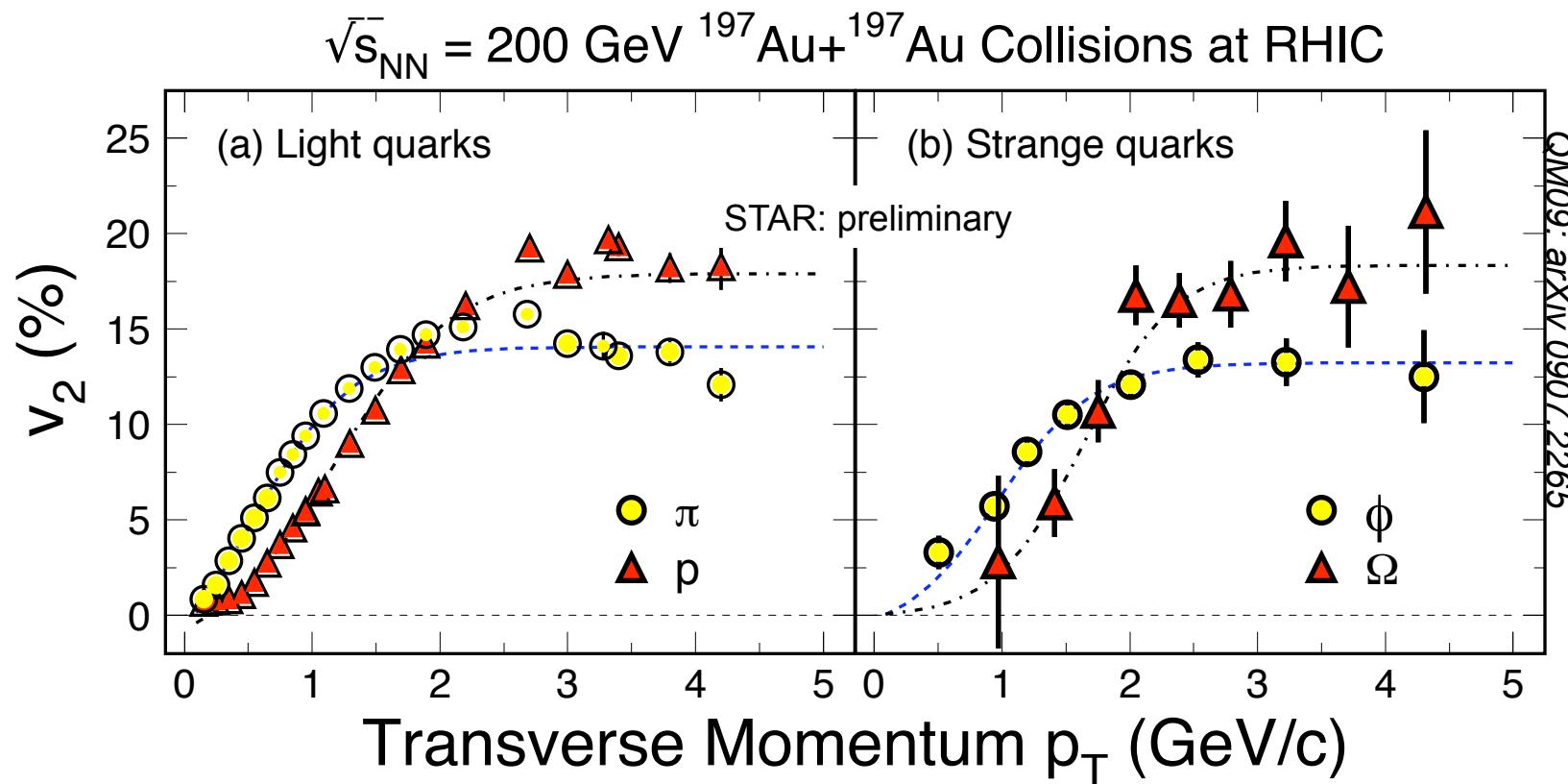


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left( \frac{p_y}{p_x} \right)$$

**Initial/final conditions, EoS, degrees of freedom**

# Partonic Collectivity at RHIC

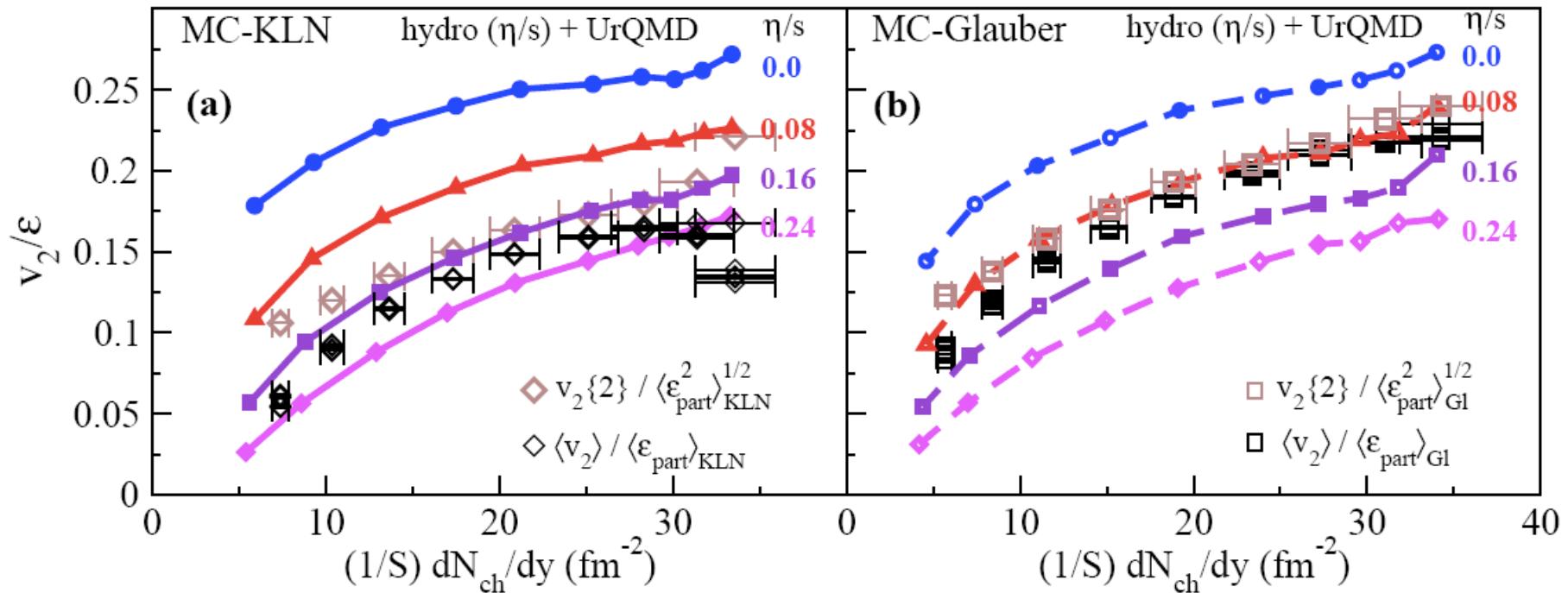


Low  $p_T$  ( $\leq 2 \text{ GeV/c}$ ): hydrodynamic mass ordering

High  $p_T$  ( $> 2 \text{ GeV/c}$ ): **number of quarks scaling**

- **Partonic Collectivity, necessary for QGP!**
- **De-confinement in Au+Au collisions at RHIC!**

# Comparison with Model



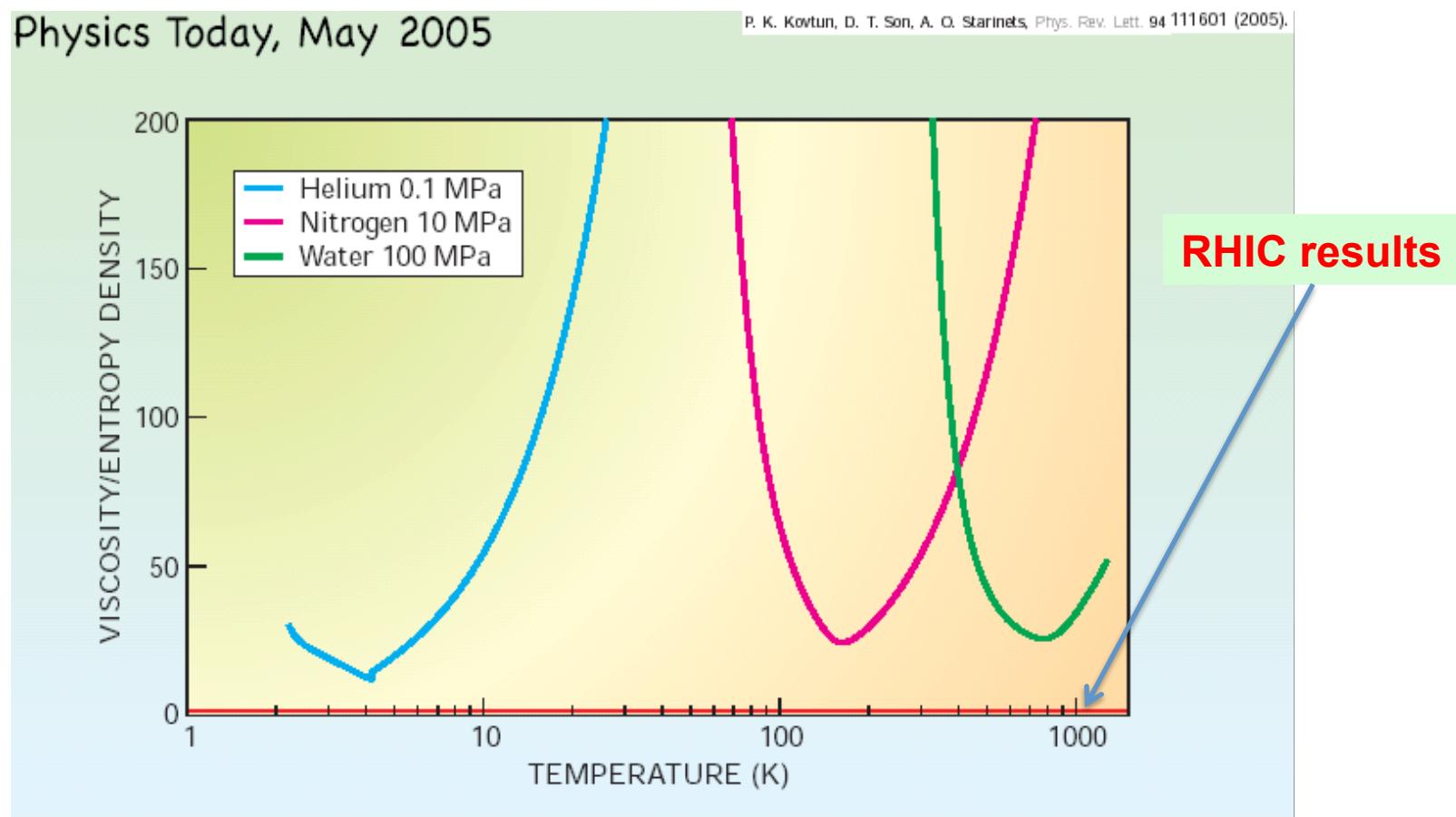
- Small value of specific viscosity over entropy  $\eta/s$
- Model uncertainty dominated by initial eccentricity  $\varepsilon$

Model: Song *et al.* *PRL*106, 192301(2011)  
*arXiv:1011.2783*

# Low $\eta/s$ for QCD Matter at RHIC

Physics Today, May 2005

P. K. Kovtun, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 94 111601 (2005).



- 1)  $\eta/s \geq 1/4\pi$
- 2)  $\eta/s(\text{QCD matter}) \ll \eta/s(\text{QED matter})$

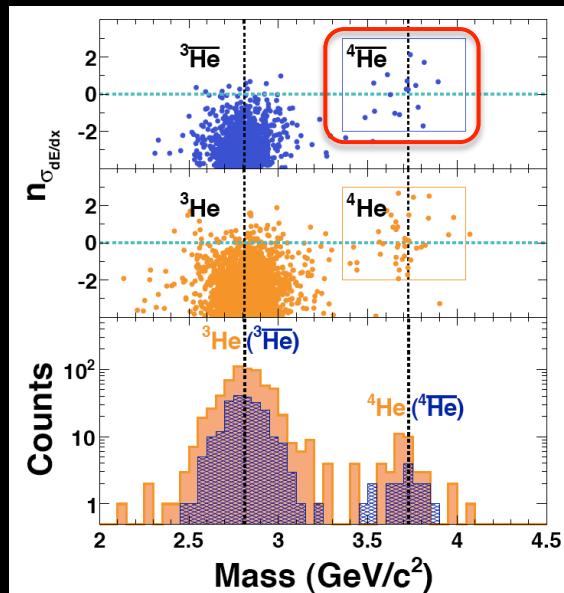
**nature**

April, 2011

***“Observation of the Antimatter Helium-4 Nucleus”***

***by STAR Collaboration***

***Nature, 473, 353(2011).***



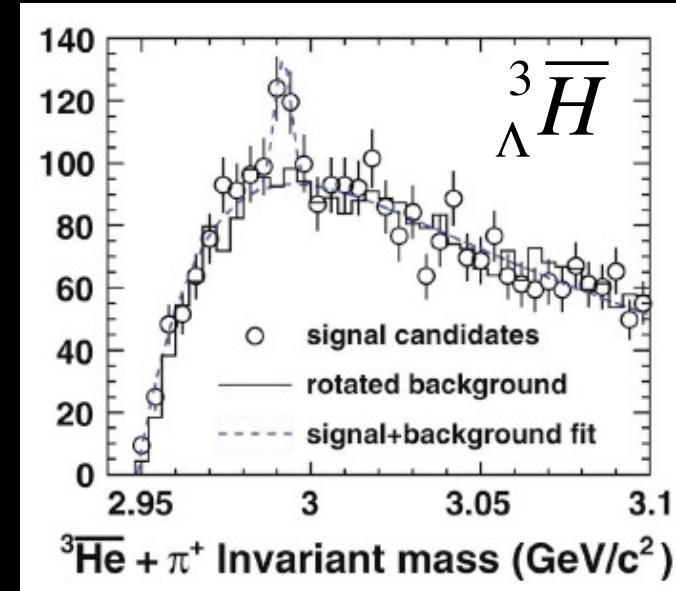
**Science**

March, 2010

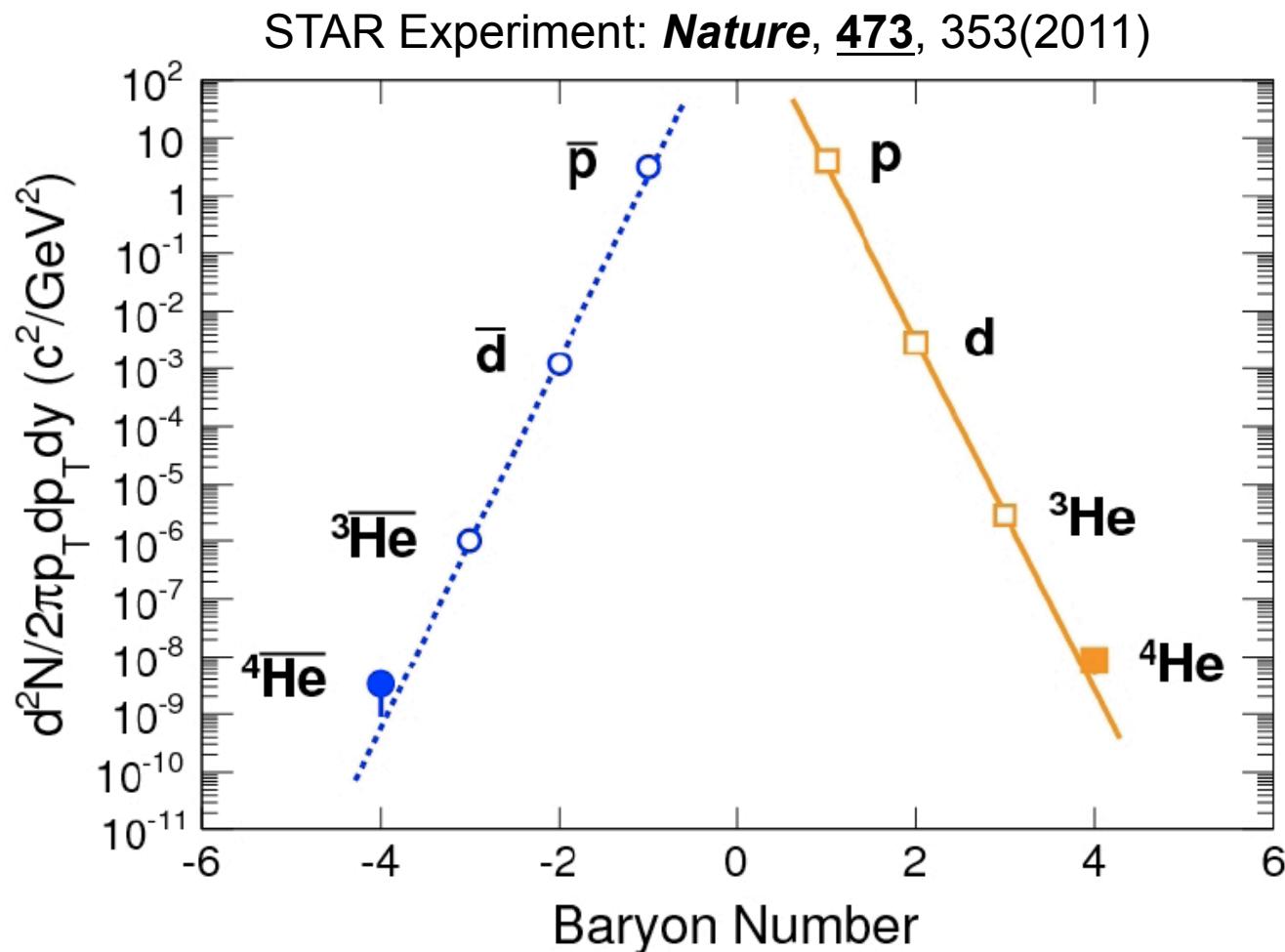
***“Observation of an Antimatter Hypernucleus”***

***by STAR Collaboration***

***Science, 328, 58(2010).***



# Light Nuclei Productions at RHIC

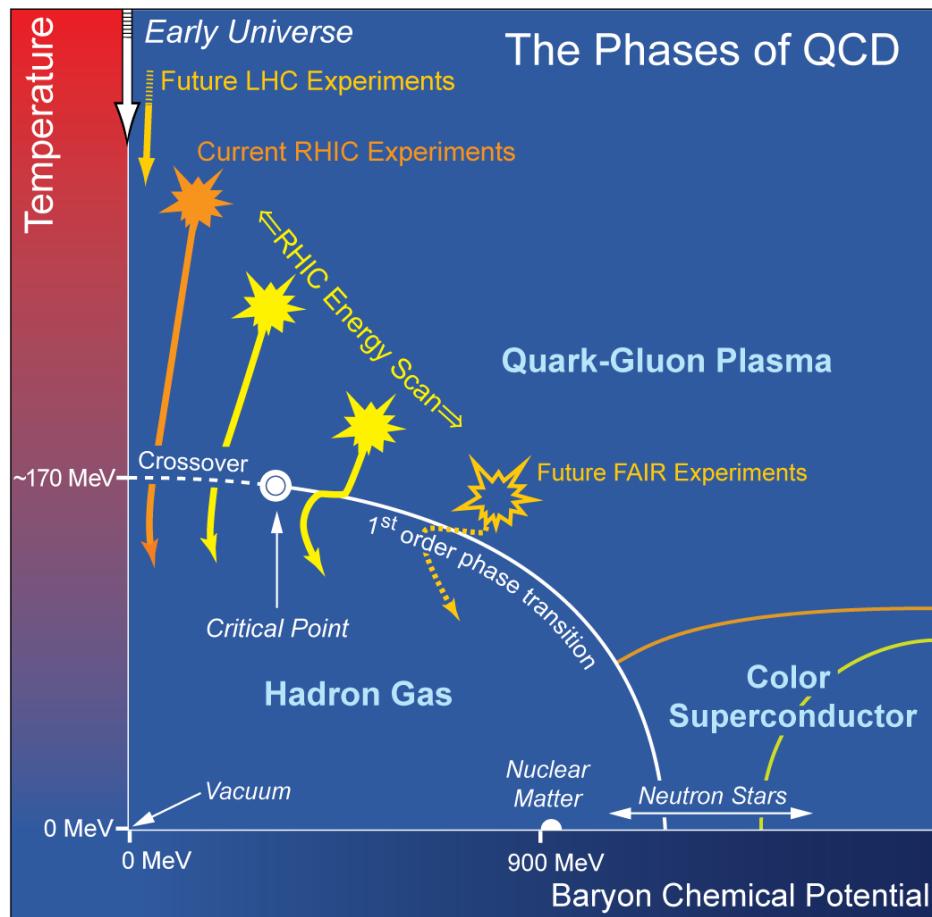


- 1) In high-energy nuclear collisions,  $N(d) \gg N(\alpha)$ :  
**sQGP → form (anti)light nuclei via coalescence**
- 2) In the Universe,  $N(d) \ll N(\alpha)$ :  $N(\text{anti-}\alpha)$ ?

# Beam Energy Scan at RHIC

## Study QCD Phase Structure

- Signals of phase boundary
- Signals for critical point

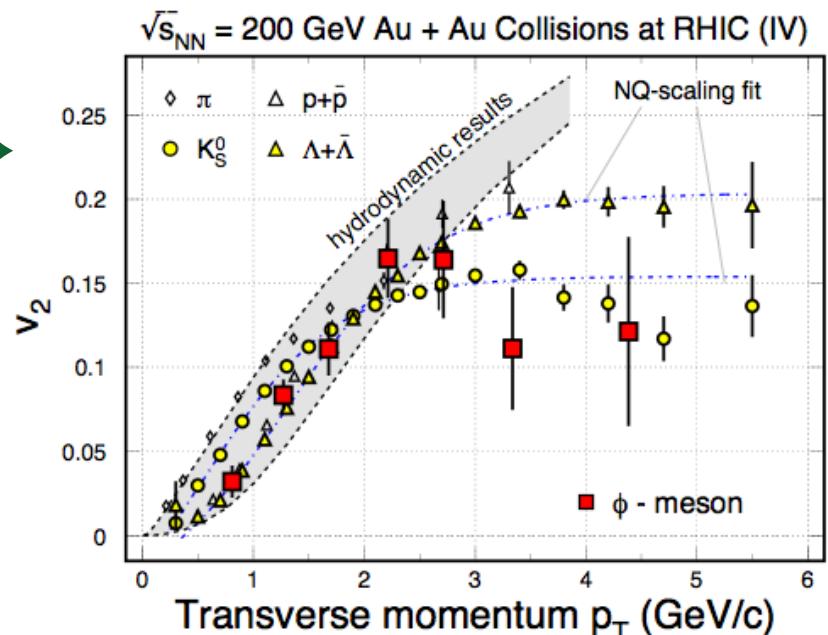
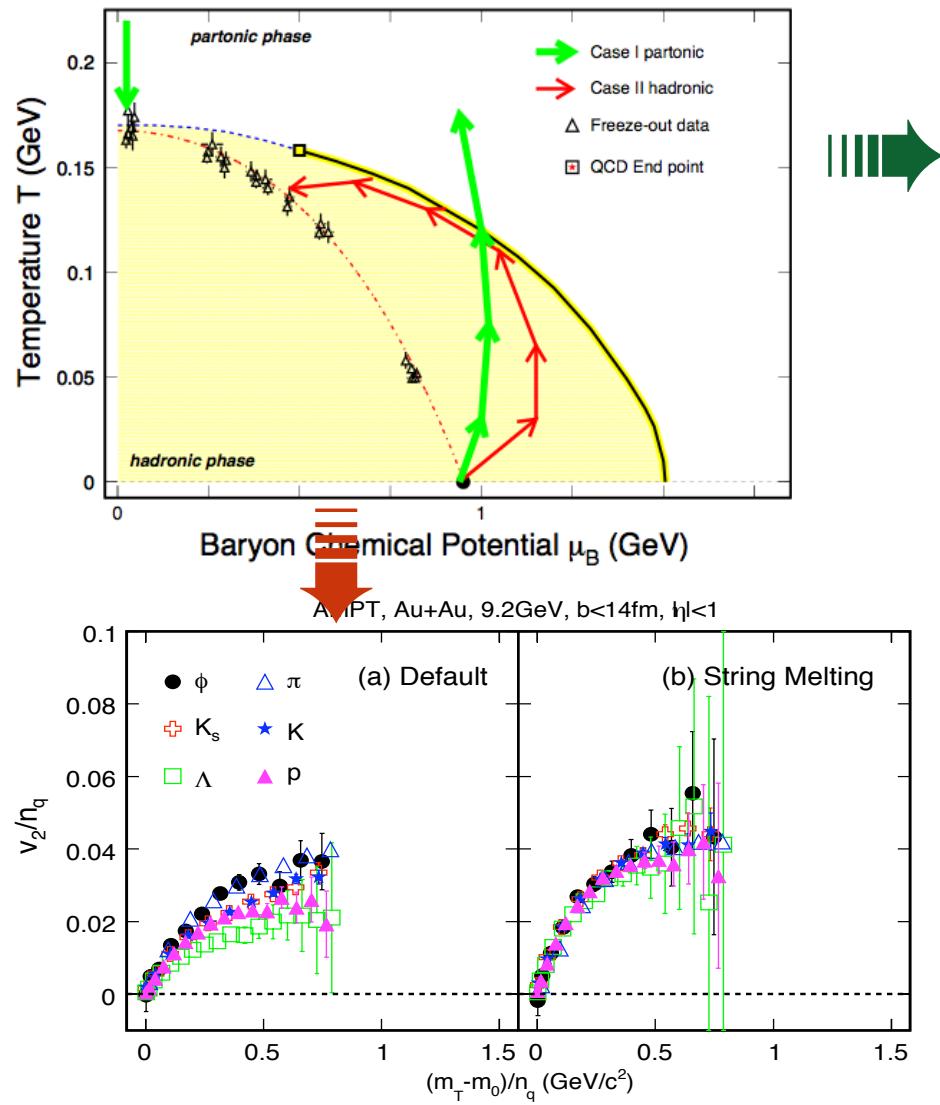


## Observations:

- (1)  $v_2$  - NCQ scaling:**  
partonic vs. hadronic dof
- (2) Dynamical correlations:**  
partonic vs. hadronic dof
- (3) Azimuthally HBT:**  
1st order phase transition
- (4) Fluctuations:**  
Critical point, correl. length
- (5) Directed flow  $v_1$**   
1st order phase transition

- <http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493>  
- arXiv:1007.2613

# Observable\*: NCQ Scaling in $v_2$



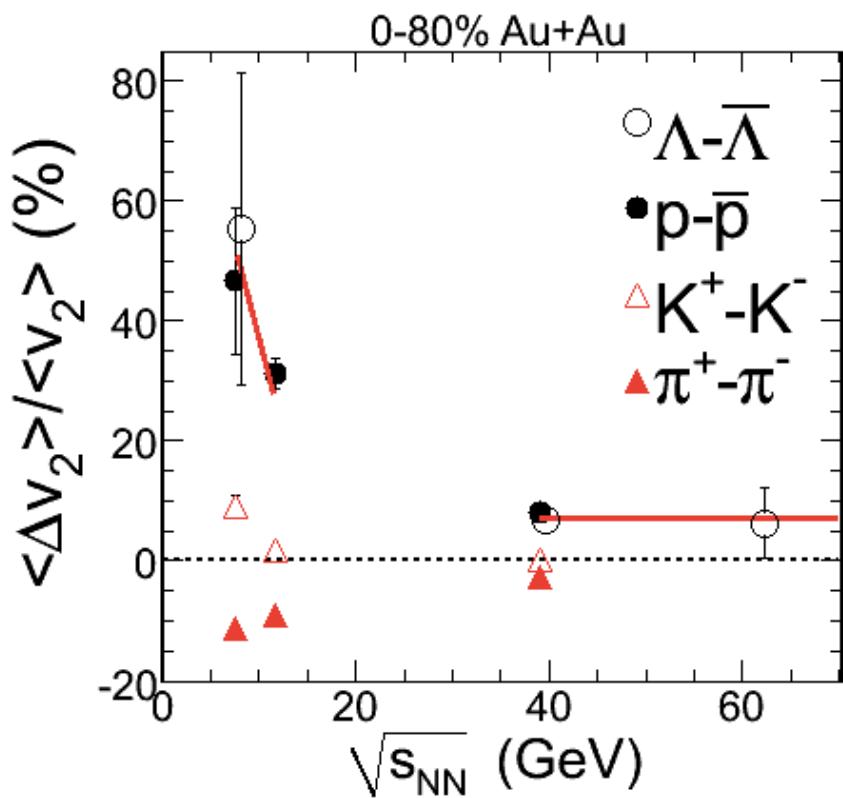
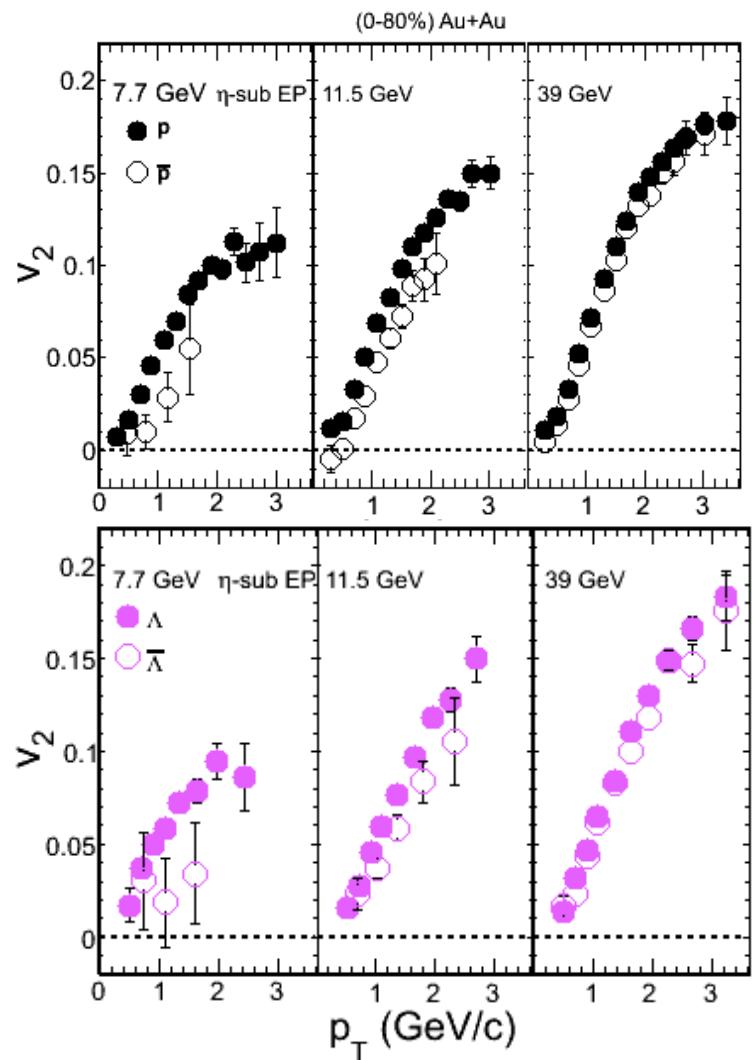
- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $s\bar{s} \Rightarrow \phi$  not  $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

**In the hadronic case, no number of quark scaling and the value of  $v_2$  of  $\phi$  will be small.**

\* Thermalization is assumed!

STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

# Particle and Anti-Particle $v_2$ vs. $\sqrt{s_{NN}}$



At  $\sqrt{s_{NN}} \leq 11.5$  GeV:

- $v_2$  (baryon) >  $v_2$  (anti-baryon)
- $v_2(\pi^+) < v_2(\pi^-)$
- $v_2(K^-) < v_2(K^+)$

STAR: Quark Matter 2011

Hadronic interactions are dominant



# Susceptibilities and Moments



Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2} \sum_i d_i (m_i/T)^2 K_2(m_i/T) \cosh[(B_i \mu_B + S_i \mu_S + Q_i \mu_Q)/T]$$

The susceptibility:  $T^{n-4} \chi_q^{(n)} = \frac{1}{T^4} \frac{\partial^n}{\partial(\mu_q/T)^n} P\left(\frac{T}{T_c}, \frac{\mu_q}{T}\right) \Big|_{T=T_c}, \quad q = B, Q, S$

$$\chi_q^{(1)} = \frac{1}{VT^3} \langle \delta N_q \rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3} \langle (\delta N_q)^2 \rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3} \langle (\delta N_q)^3 \rangle$$

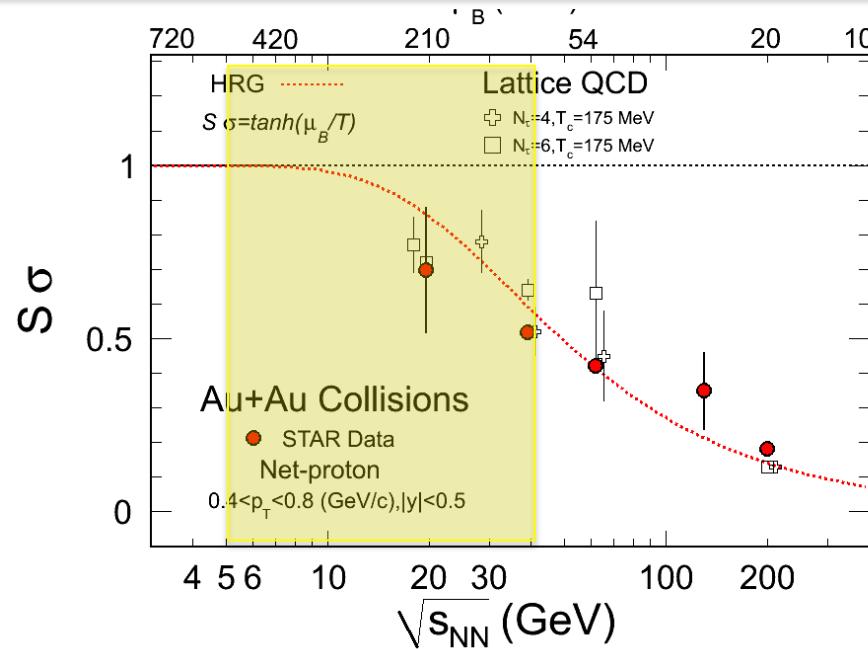
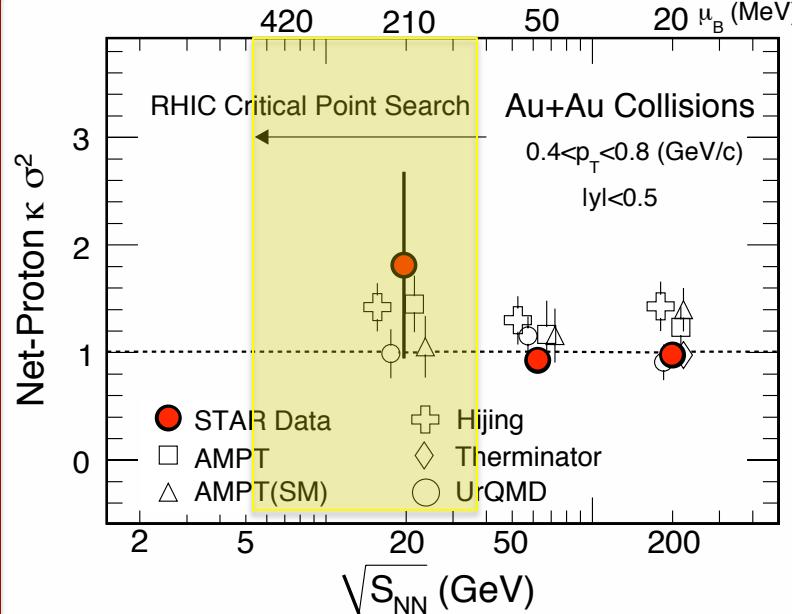
$$\chi_q^{(4)} = \frac{1}{VT^3} \left( \langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2 \right)$$

$$\begin{aligned} \frac{T^2 \chi_q^{(4)}}{\chi_q^{(2)}} &= \kappa \sigma^2 \\ \frac{T \chi_q^{(3)}}{\chi_q^{(2)}} &= S \sigma \end{aligned}$$

Conserved  
Quantum  
Number

Thermodynamic function  $\Leftrightarrow$  Susceptibility  $\Leftrightarrow$  Moments  
**Model calculations, e.g. LGT, HRG  $\Leftrightarrow$  Measurements**

# High Moments: Critical Point Search



- Measure conserved quantities,  $B$ ,  $s$ , and  $Q$
- First: High order fluctuation results consistent with thermalization
- First: Tests the *long distance QCD* predictions in hot/dense medium

**Caveats:** (a) static vs. dynamic; (b) net-B vs. net-p; (c) potential effects of freeze-out...

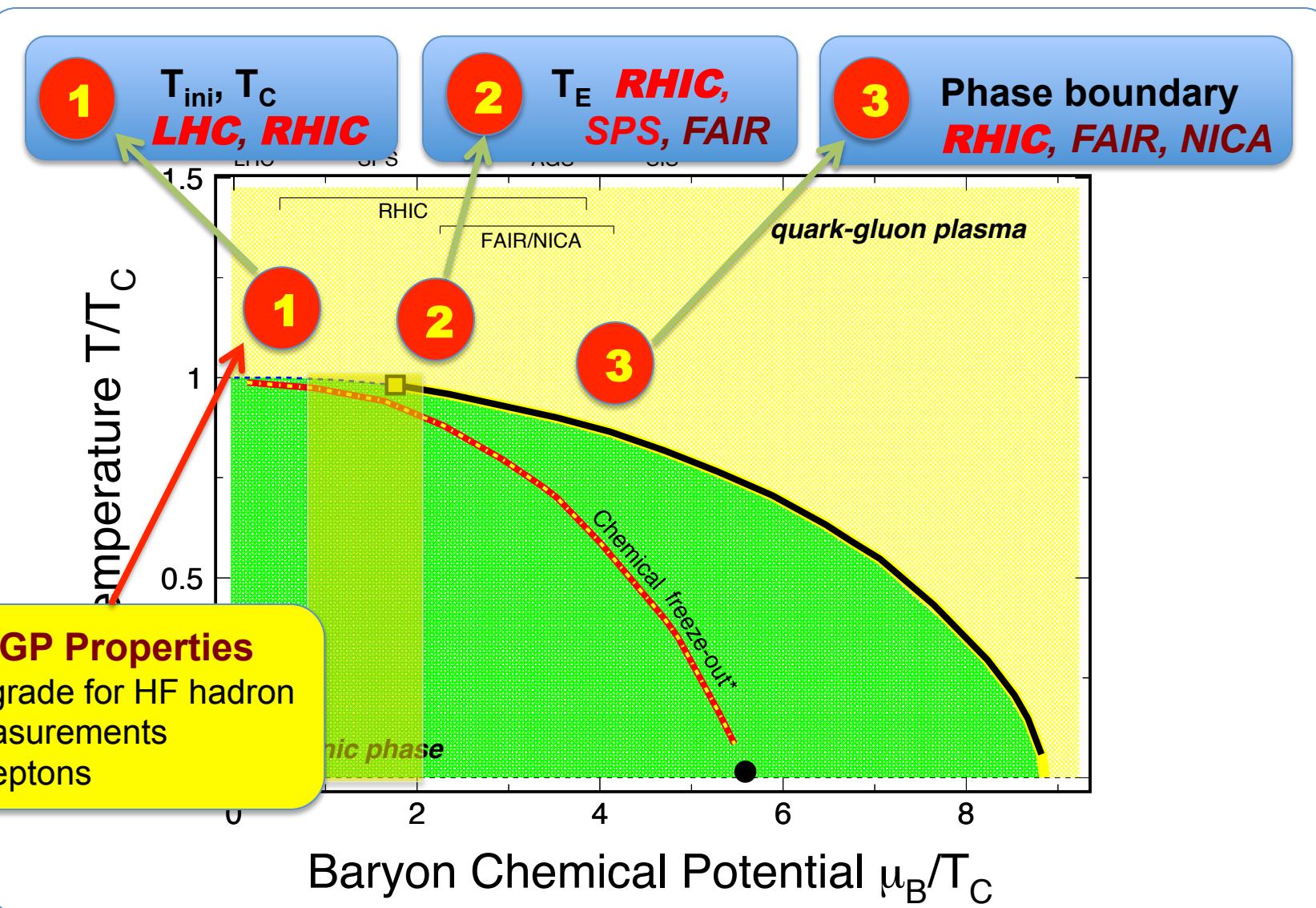
- R. Gavai, S. Gupta, 1001.3796 / F. Karsch, K. Redlich, 1007.2581 / M. Stephanov, 0911.1772.
- STAR: PRL105, 02232(2010) and references therein.



# Summary on Selected Results

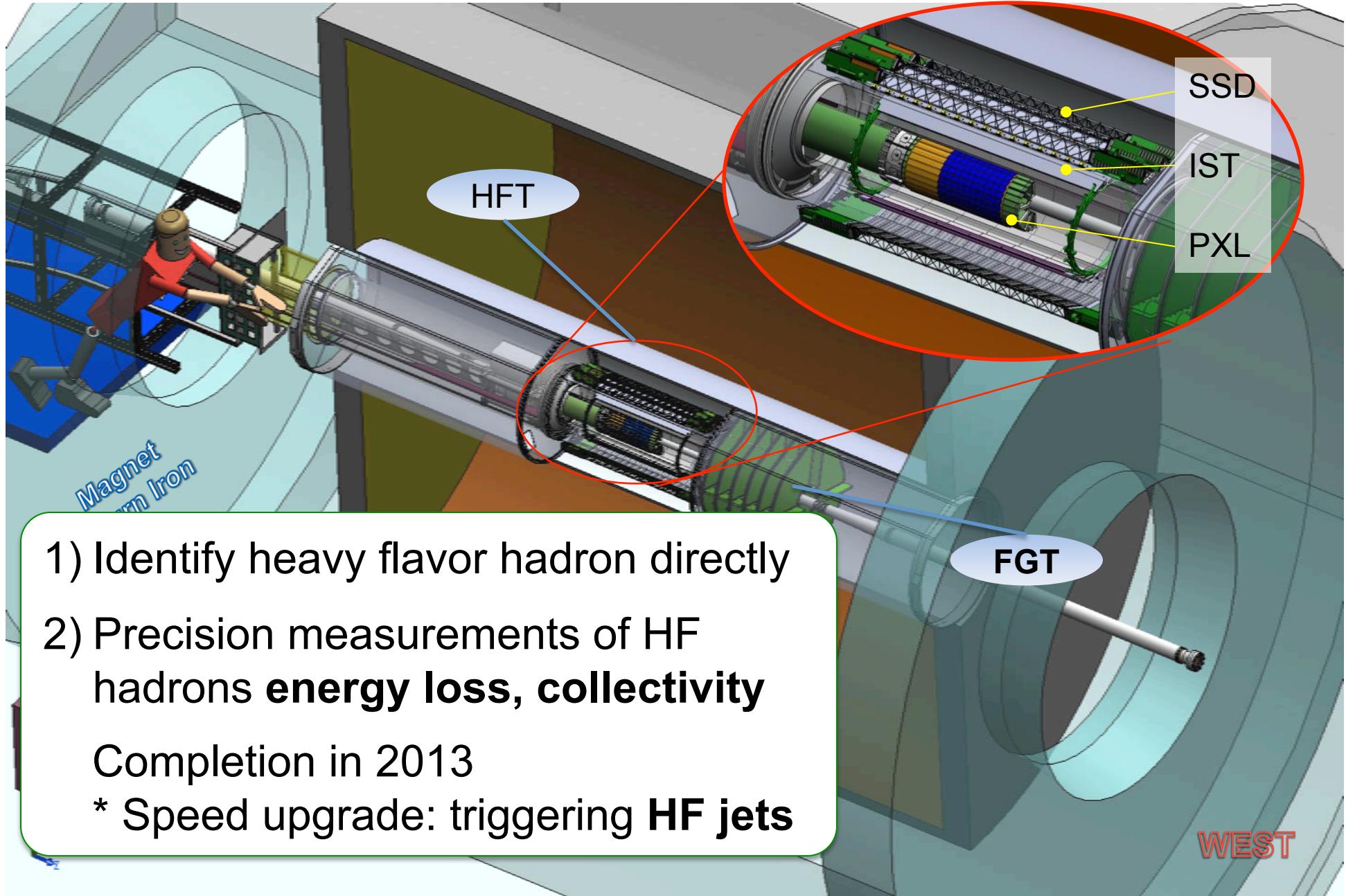


- (1) Spin: lots of progresses have been made in understanding proton helicity structure
- (2) In high-energy nuclear collisions, hot and dense ***matter, with partonic degrees of freedom and collectivity***, has been formed:
  - Matter behavior like a *quantum liquid* with small  $\eta/s$  ( $_{^3\Lambda}H, _{^3\Lambda}He$ )
  - Partonic matter → antimatter:
- (3) **BES**: [partonic]  $< \mu_B \sim 110\text{--}320 \text{ (MeV)}$  < [hadronic]
- (4) Net-proton distributions are consistent with LGT results. Crossover temperature:  $T_C = 175^{+1}_{-7} \text{ (MeV)}$

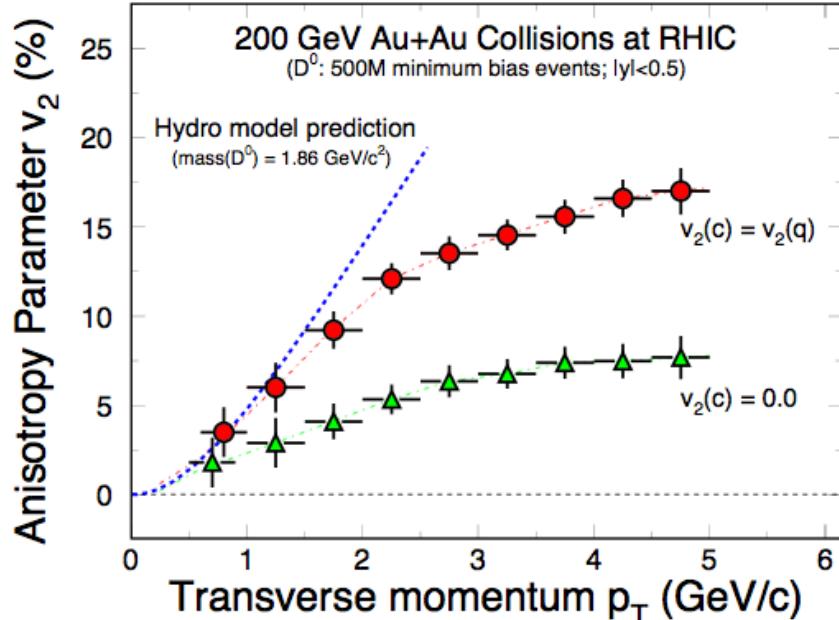




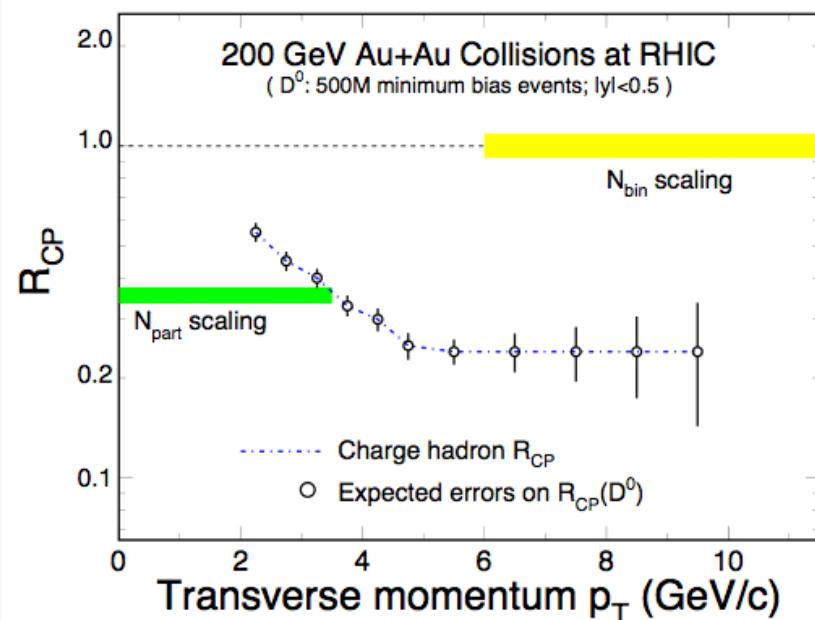
# Heavy Flavor Tracker (HFT) at STAR



# HFT: Charm Hadron $v_2$ and $R_{AA}$

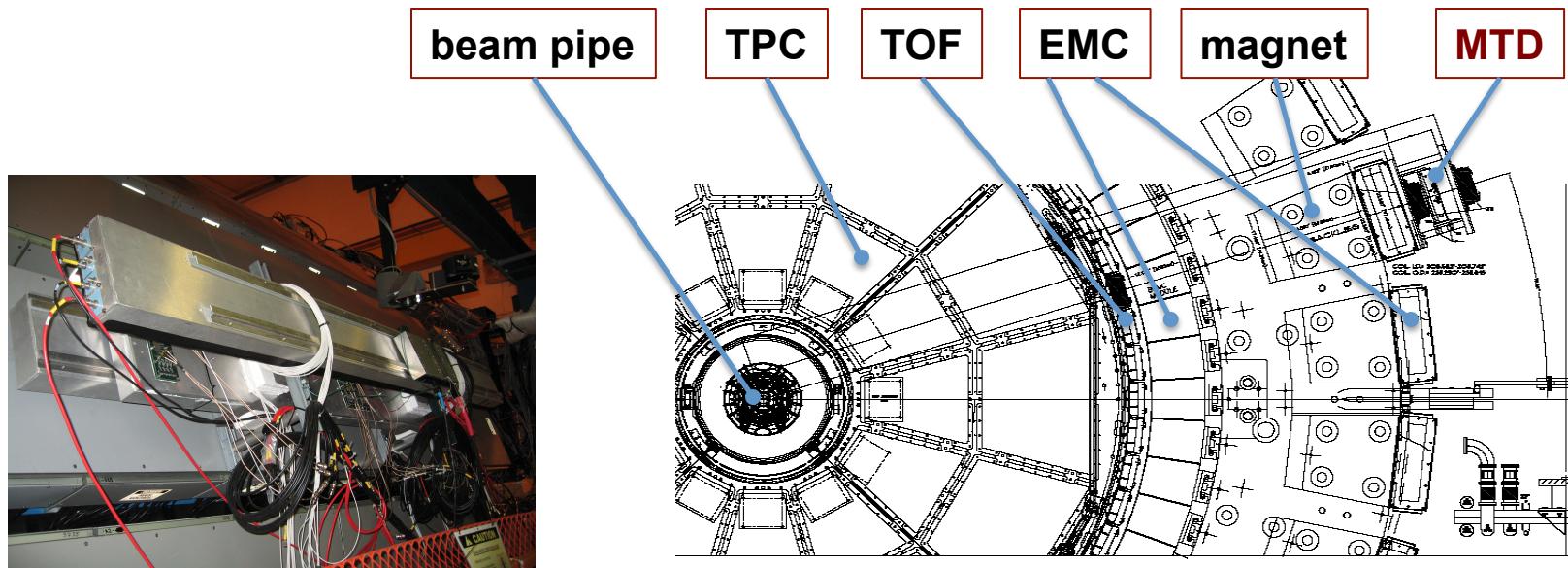


- 200 GeV Au+Au m.b. collisions (500M events).
- Charm hadron collectivity  $\Rightarrow$  drag/diffusion constants  $\Rightarrow$
- Medium properties!**
- Light quark thermalization!**



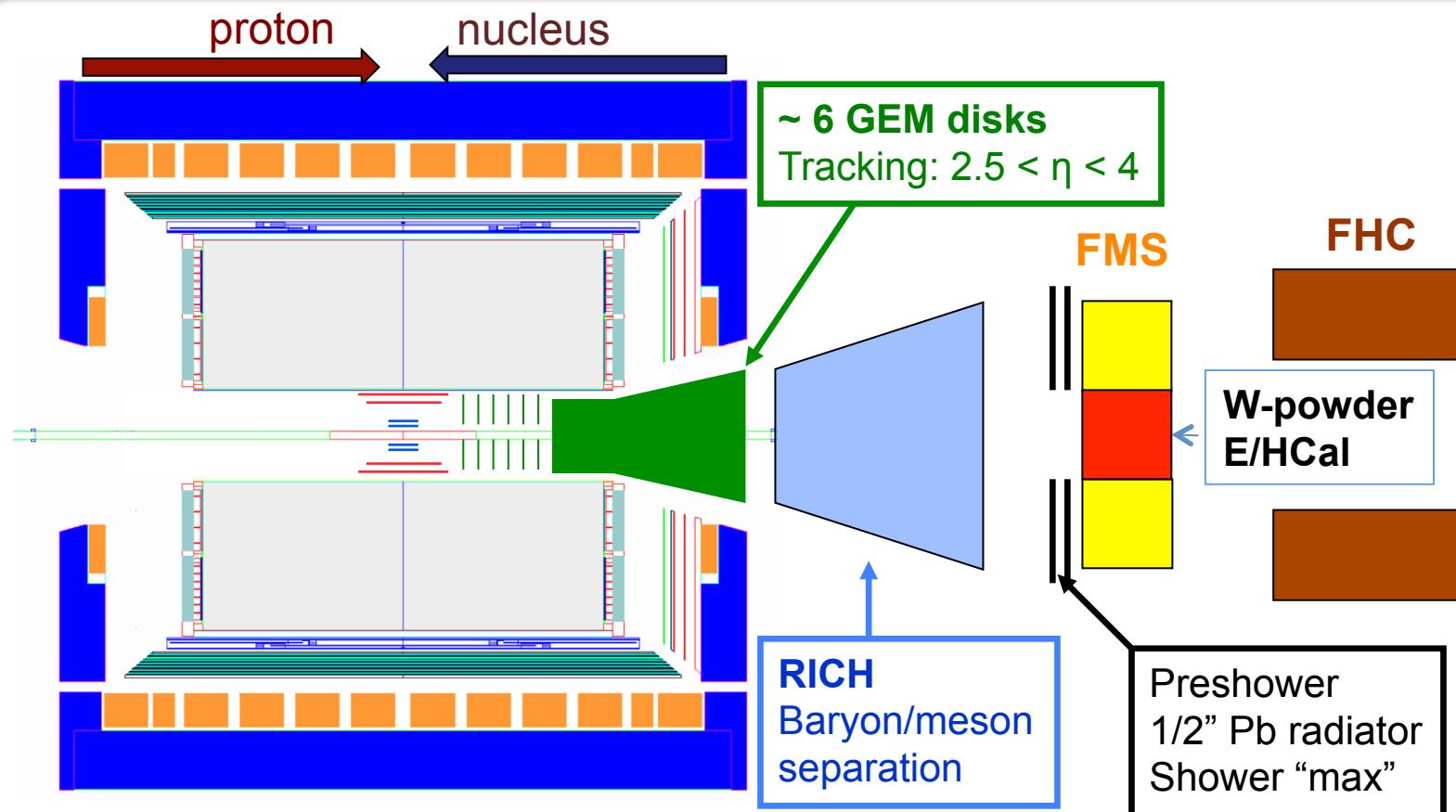
- 200 GeV Au+Au m.b. collisions ( $|y|<0.5$  500M events)
- Charm hadron  $R_{AA} \Rightarrow$
- Energy loss mechanism!**
- QCD in dense medium!**

# STAR: Muon Telescope Detector



## Muon Telescope Detector (MTD) at STAR:

- 1) MRPC technology;  $\mu_\varepsilon \sim 45\%$ ; cover  $\sim 60\%$  azimuthally and  $|y| < 0.25$
- 2) TPC+TOF+MTD: muon/hadron enhancement factor  $\sim 10^{2-3}$
- 3) For high  $p_T$  muon trigger, heavy quarkonia, light vector mesons,  $B \rightarrow J/\Psi + X$
- 4) China-India-STAR collaboration: completion in 2013

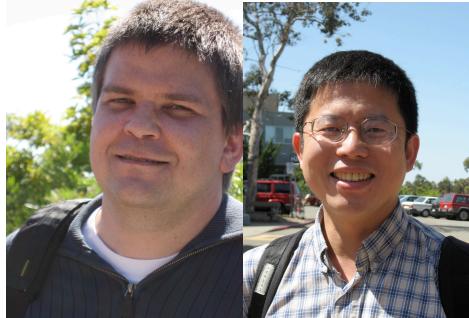


**Forward instrumentation** optimized for  $p+A$  and **transverse spin** physics

- Charged-particle tracking
- $e/h$  and  $\gamma/\pi^0$  discrimination
- Baryon/meson separation
- DY measurements

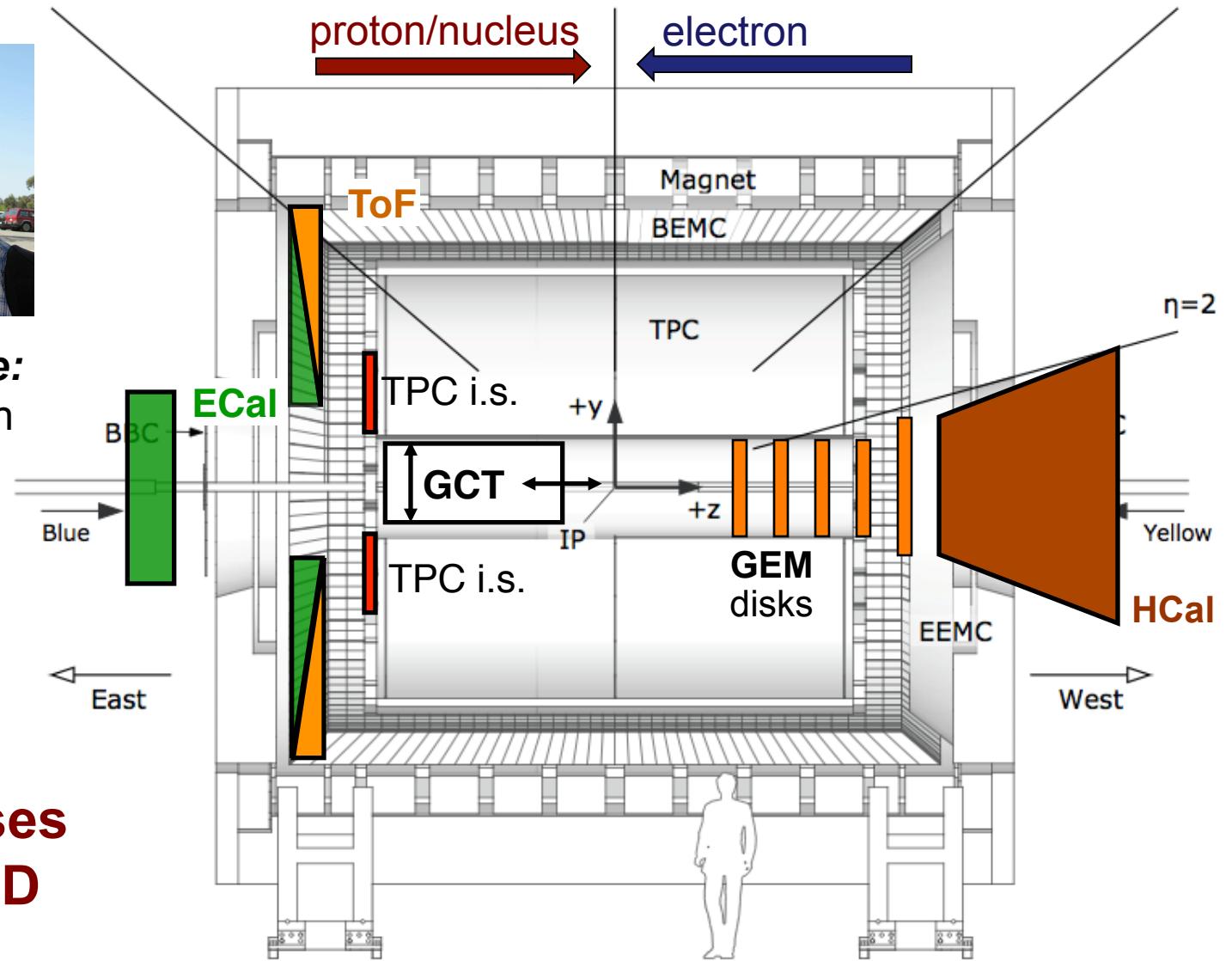
**~ 2016**

# Outlook: from *STAR* to *eSTAR*



## **eSTAR Task Force:**

- Ernst Sichtermann
- Zhangbu Xu



- Science Cases**
- Detector R&D**

INT Report: arXive: 1108.1713



# Summary



- 1) RHIC: Dedicated facility for studying matter with QCD degrees of freedom:
  - *Properties of QGP*
  - *Sea quark and gluon contributions to proton helicity structure*
  - *QCD critical point and phase boundary*
- 2) Future: EIC (eRHIC, 2022 - ...)
  - *Partonic structures of nucleon and nuclei, i.e. nPDF*
  - *Dynamical evolution from cold nuclear matter to hot QGP*

## Phase Structures of **QCD** Matter

*Many Thanks to the  
Organizers!*

**Nu Xu**



## Summary II:



### sQGP formation at 200 GeV

- (1) In high-energy nuclear collisions, hot and dense ***matter***, with ***partonic degrees of freedom*** and ***collectivity***, has been formed
- (2) The matter behavior like a ***quantum liquid*** with small  $\eta/s$
- (3) Partonic matter → antimatter:  ${}^3\bar{H}$ ,  ${}^4\bar{He}$

**What is the structure of the QCD matter?**



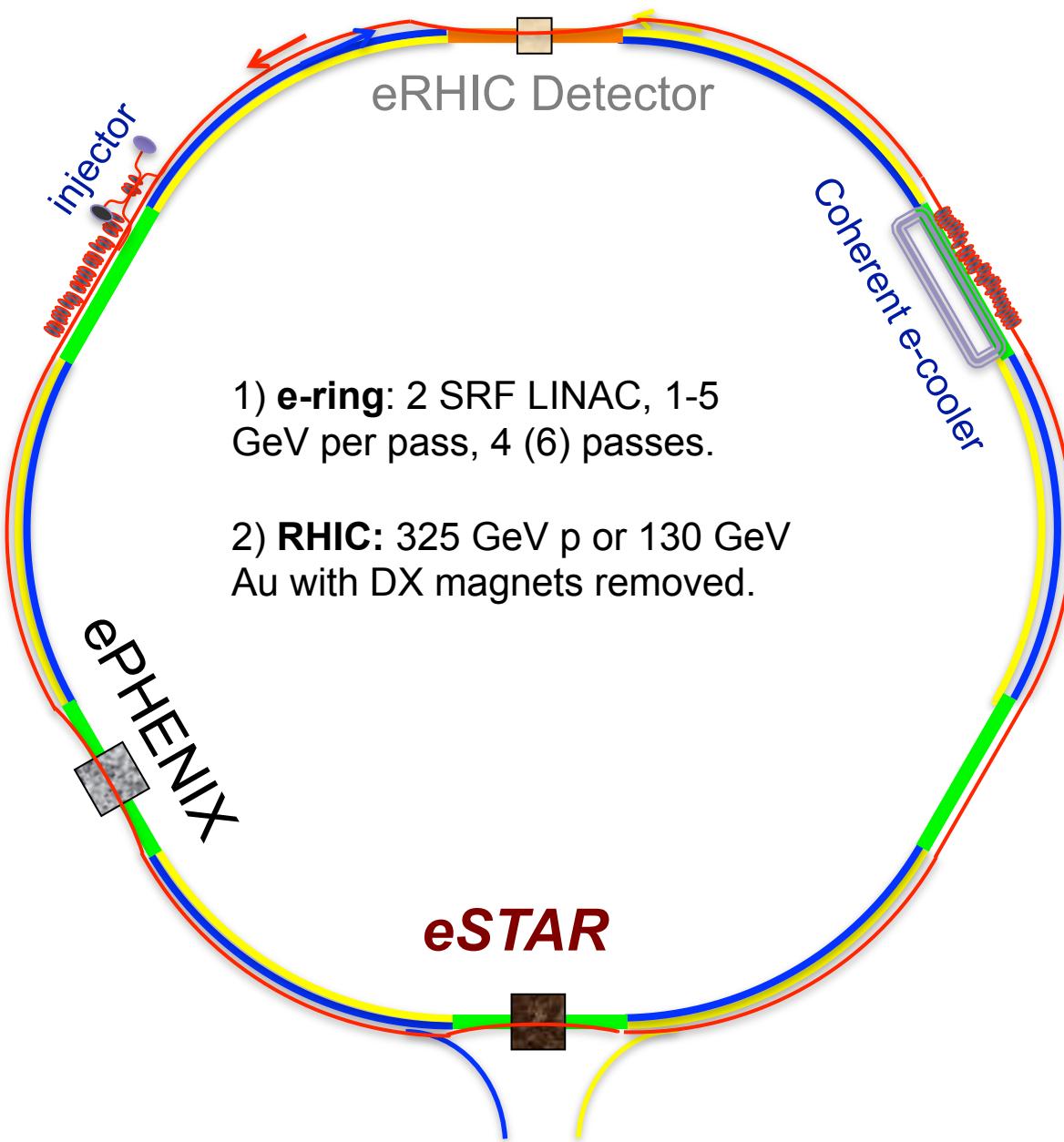
# Summary II: NCQ-Scaling in $v_2$



- 1) Partonic collectivity in 200 GeV collisions
  - 2) At  $\sqrt{s_{NN}} \leq 11.5$  GeV
    - $v_2(\text{baryon}) > v_2(\text{anti-baryon})$
    - $v_2(\phi) < v_2(\text{hadron})$
- $v_2$ -NCQ-scaling broken
- [hadronic]  $\otimes \sqrt{s_{NN}} \leq 11.5$  GeV
- [partonic]  $\otimes \sqrt{s_{NN}} \geq 39$  GeV

## Where is the critical point?

# Outlook: eRHIC



**eRHIC:**  
(2022-2025)

e beam: 20-30 GeV  
p beam: 325 GeV  
ion beam: 130 GeV  
1 dedicated detector

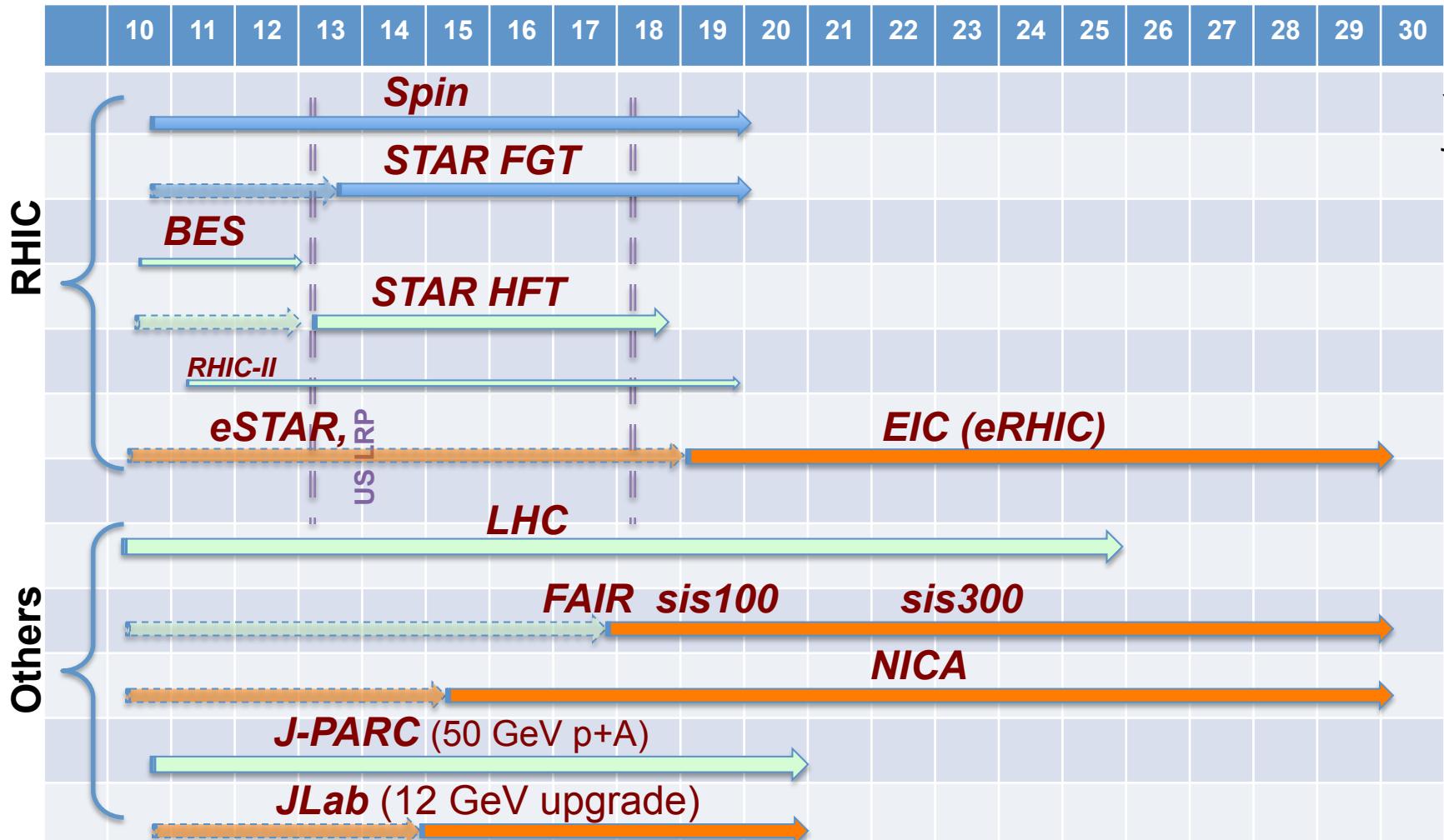
**ePHENIX/eSTAR:**  
(2018-2022)

e beam: 5 GeV  
p beam: 325 GeV  
ion beam: 130 GeV

S. Vigdor: 2010 RHIC operational review

# Timeline of QCD Facilities

Nu Xu, September 2009



# Non-Gaussian Fluctuations

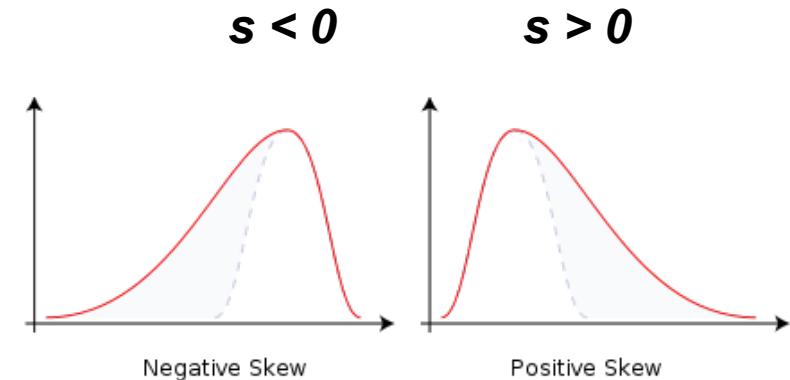
$N$ : event by event multiplicity distribution

$$m = \langle N \rangle$$

$$\sigma = \sqrt{\langle (N - \langle N \rangle)^2 \rangle}$$

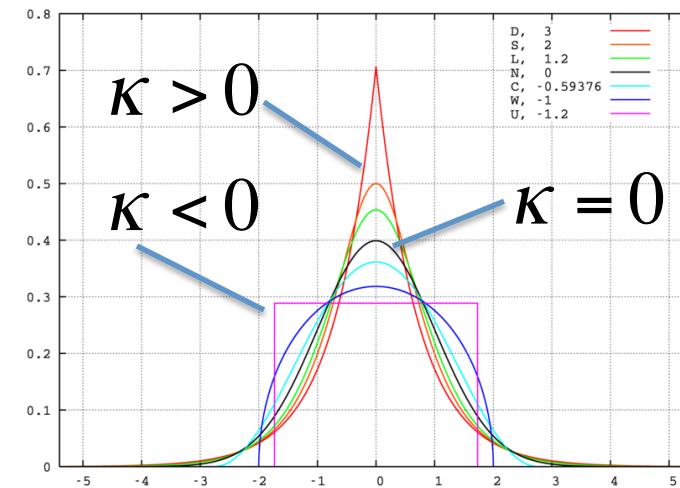
$$s = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\sigma^3}$$

$$\kappa = \frac{\langle (N - \langle N \rangle)^4 \rangle}{\sigma^4} - 3$$



For a Gaussian distribution, the  $s=0$ ,  $\kappa=0$ . **Ideal probe of the non-Gaussian fluctuations at critical point.**

Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena.**  
Price: large number of events required.



# Physics of the Heavy Flavor Tracker at STAR

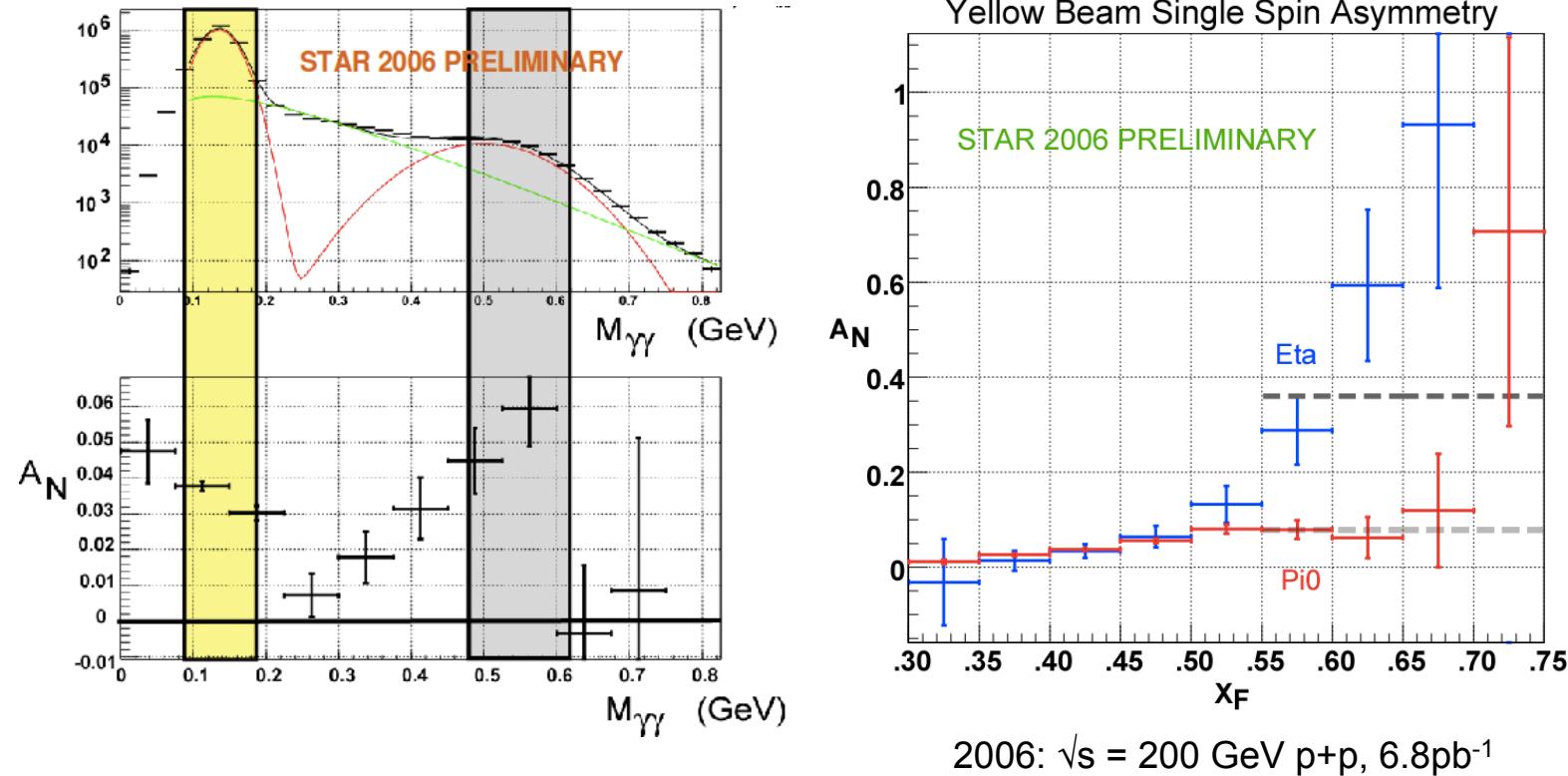
## 1) Direct HF hadron measurements (p+p and Au+Au)

- (1) Heavy-quark cross sections:  $D^{0,\pm,*}$ ,  $D_S$ ,  $\Lambda_C$ ,  $B$ ...
- (2) Both spectra ( $R_{AA}$ ,  $R_{CP}$ ) and  $v_2$  in a wide  $p_T$  region: 0.5 - 10 GeV/c
- (3) Charm hadron correlation functions, heavy flavor jets
- (4) Full spectrum of the heavy quark hadron decay electrons

## 2) Physics

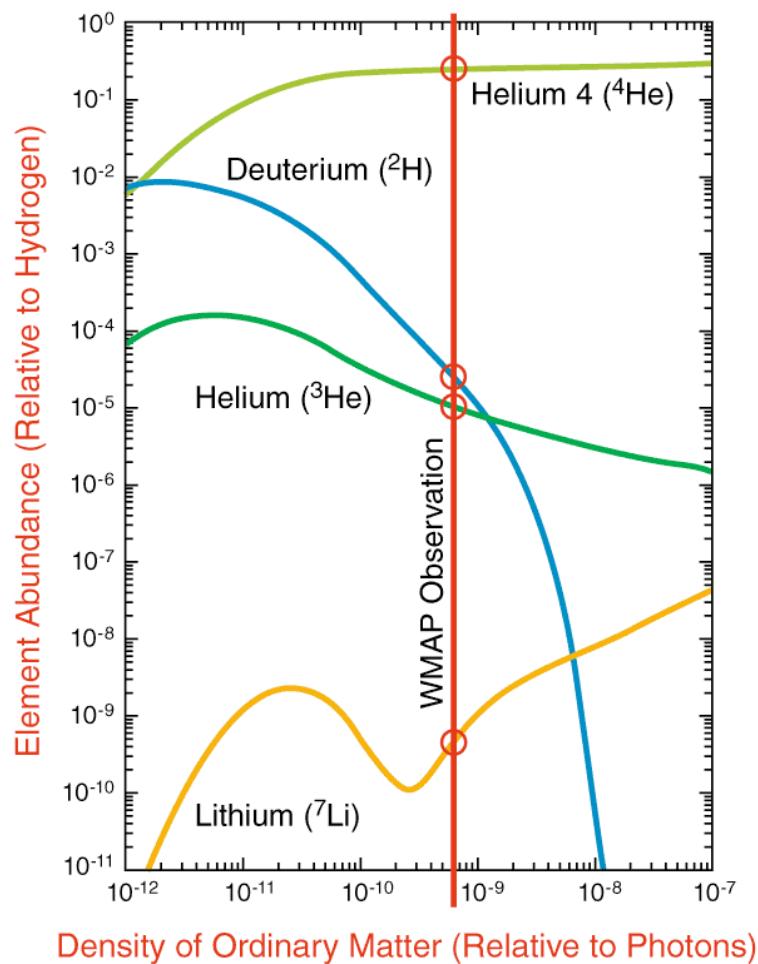
- (1) Measure heavy-quark hadron  $v_2$ , heavy-quark collectivity, to study the medium properties **e.g. *light-quark thermalization***
- (2) Measure heavy-quark energy loss to study pQCD in hot/dense medium  
**e.g. *energy loss mechanism***
- (3) Measure di-leptons to study the ***direct radiation*** from the hot/dense medium
- (4) Analyze ***hadro-chemistry including heavy flavors***

# Single Spin Asymmetry $A_N$ of $\pi^0$ , $\eta$



- At  $x_F = 0.55$ ,  $\langle \eta \rangle \sim 3.7$ ,  $A_N(\eta) > A_N(\pi^0)$  has been observed
- Production cross section for both mesons are under study

# Atomic Nuclei Formation



NASA/WMAP Science Team  
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy  
and Astrophysics (Institute of Physics) December, 2000

$$\frac{n_B}{n_\gamma} \approx 10^{-9}$$

